An Empirical Formula to Classify the Quality of Earthquake Locations

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Abstract

Providing a quantitative estimate of earthquake location quality is not a simple task. Traditional methods, used in literature, are not exhaustive and depend on a subjective point of view, since they consist of empirical choice of quality thresholds of different estimators of location uncertainty. However, we notice that these estimators are correlated with each other, implying the need to combine them in order to obtain a numerical and impartial estimate of the quality of a seismic location. Therefore, we provide a formula that associates a quality factor (q_f) value with a seismic location, which is based on the combination of a set of uncertainty estimators, suitably normalized. We apply the criterion to two different-type and -scale earthquake catalogs, located by two different methods, obtaining encouraging results.

The q_f parameter definition is a fast, simple and objective instrument to provide a user-friendly classification of location quality. Thus, the q_f could represent a powerful tool for routine monitoring location computation.

Introduction

Seismotectonic and seismic hazard studies, as well as “real-time” seismic notifications and nuclear test monitoring, induced and geothermal seismicity, should be assessed with an exhaustive description of the earthquake location accuracy and with a thorough understanding of location uncertainties. The methods to locate an earthquake are generally divided in linearized approaches, like those implemented in the codes Hypo71, Hypoellipse and HypoDD (Lee and Lahr, 1975; Lahr, 1989; Waldhauser, 2001), and global search methodologies, e.g., probabilistic schemes implemented in the NonlinLoc code (Lomax et al., 2000, 2009) and in NLDiffLoc (De Landro et al., 2015).

Regardless of the method applied to locate an earthquake hypocenter, the validity of the solution is generally assessed "a posteriori" by analyzing the uncertainty estimators associated with the inversion results like the root mean square error, the number of phases used for the inversion, the azimuthal gap, the error on the horizontal and vertical hypocentral coordinates. A standard procedure usually consists in classifying the location results using fixed, reasonable ranges, of such uncertainty estimators, which are empirically chosen. For instance, the Hypo71 code provides a quality classification, based on fixed ranges. Usually, these robustness ranges are tuned considering the system-scale, the density of information (e.g., the earthquake-station geometry) and according to data fit and formal errors (see for example Amato and Mele, 2008). Some earthquake location studies, based on direct-search methods, try to assess the reliability of the locations by using the so-called network criteria, which include measures derived from either the geometry of the stations that recorded the earthquake and/or the data fit. Several studies (see for example Bondar et al. 2004, and references therein) used these geometrical criteria to characterize well-constrained hypocenter locations.

Although different methods exist, it is still an unsolved problem to establish an exhaustive and quantitative criterion that, on one hand, does not need any “a priori” empirical selection of goodness ranges of uncertainty estimators, and that, on the other hand, provides a simple and accessible classification of earthquake location.

In this paper, we propose a criterion, that combines different uncertainty estimators, associated with different both “a priori” and “a posteriori” characteristics of a hypocenter, such as the network density and the earthquake-station geometry. We suggest an empirical formula which combines the uncertainty estimators provided by location codes to obtain a quality factor $q_{f.}$ This factor can be used to group elements in an earthquake catalog in different suitable quality classes according to the q_f value.

In order to test the efficiency of q_f term, we applied the criterion to two Italian earthquake catalogs, with different scale size and different seismicity rate (sequence and background), obtained with two location methods. Catalog-1 includes earthquakes of a seismic sequence, confined at crustal scale and located by the global search code Nonlinloc; catalog-2 includes earthquakes occurred at regional and lithospheric scale (down to 600 km depth) and located by the Ipop code (Basili et al., 1984). The latter is based on a linearized inversion method and is routinely used in the Italian National monitoring room at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), and for the compilation of the INGV seismic bulletin (Amato and Mele, 2008, and references therein).

We want to demonstrate the efficiency of our approach by applying the q_f criterion to these two cases-studies. Moreover, we discuss the impact of its use for “a posteriori” analyses and interpretations of seismicity catalogs in different seismotectonic contexts.

Method

The first step of our analysis is based on the selection of the uncertainty estimators to be used. We start from the most common estimators binding the accuracy and the precision of a seismic location. In general, we observe that some uncertainty estimators, as the number of phases (NPHS), can be evaluated a priori, as it depends on both data availability and network geometry. The NPHS estimator represents a crucial point of our analysis because a large number of useful recordings usually better constrain the hypocenter position. Other estimators, useful to obtain insights about the accuracy of a seismic location, are instead more related to the inversion results. Commonly used estimators are the root mean square (RMS), that summarizes the deviation between computed and observed travel-times, the GAP, that corresponds to the maximum azimuthal angle between two successive stations around the source epicenter, that provides information about the geometric coverage of the network, significantly controlling the epicentral resolution, and the formal errors on the horizontal (ERH) and vertical (ERZ) hypocentral coordinates, which are generally derived from the covariance matrix under certain assumptions on the data error. Such estimators can be used for classifying results from both global and linearized hypocenter locations methods.

Since a probabilistic location approach provides a probability density function (pdf) for the hypocenter, in such case, additional estimators can be derived to further characterize the uncertainty of the location. A first estimator is the distance between the pdf expected value and its maximum likelihood (LOCDIST) that provides information about the symmetry of the pdf distribution (Husen and Smith, 2004). A second estimator (PDFRAD) represents the radius of a sphere having volume equivalent to that recovered by the scatter points (i.e., samples of the pdf distribution), providing information about the most likely region for the maximum likelihood hypocenter and how much confined or diffuse the probability distribution is (Lomax et al., 2009).

Once the uncertainty estimators have been identified, we preliminarily clean the datasets for the possible outliers adopting the classical Chauvenet criterion (Taylor, 1997).

Then, the estimators need to be normalized in order to legitimize the combination of different physical quantities. All estimators, but NPHS, are normalized to their maximum value, since the larger are the estimators the less constrained is the location. On the other hand, the NPHS estimator shows a different behavior since, in general, the larger is the available number of phases the most constrained should be the solution. Since, our datasets exhibits a hyperbolic behavior for this estimator (Figure 1), we non-dimensionalize it as the ratio between the median NPHS value and the current one.

Finally, in its most general form, we define the quality factor q_f for the i-th event as

$$q_f(i) = \left(\frac{w_1 RMS_n(i)^2 + w_2 NPHS_n(i)^2 + w_3 GAP_n(i)^2 + w_4 ERH(i)^2 + w_5 ERZ_n(i)^2 + w_6 DISTLOC_n(i)^2 + w_7 PDFRAD(i)^2}{N_{est}}\right)^{\frac{1}{2}} \quad (1)$$

where the subscript n means "normalized". In equation 1, w_j are the weights that could be eventually associated with each estimator, depending on the case study. In the applications presented in this article, we assumed w_j equal to 1 for all the estimators. N_{est} represents the number of the actually employed estimators, e.g., N_{est} is equal to 7 if all the weights estimators in equation 1 are non-zero.

The q_f value, defined in equation 1, ranges between 0 and 1, moving from the optimal location toward the worst one. The values of q_f can be further used to define some more user-friendly classification. Here, we consider four different quality classes for four evenly spaced intervals: A-class for $q_f \leq 0.25$, B-class for $0.25 < q_f \leq 0.5$, C-class for $0.5 < q_f \leq 0.75$, and D-class for $q_f > 0.75$. However, the thresholds among the classes could be conveniently modified by the operator, for instance, through a preliminary analysis on the catalog. It is worth noting that, when an outlier has been identified in the uncertainty parameters database through the Chauvenet criterion, the corresponding location is automatically assigned to the D-class.

Data

Since uncertainty estimators associated with hypocenter locations could be different depending on the approach adopted for the inversion (i.e., linearized vs. global), we analyze two different study cases, in order to demonstrate the suitability of our criterion for earthquake location results obtained with both the approaches.

As an example of a very high-density seismicity area, we used a catalog (Catalog-1) consisting of 32,773 crustal earthquakes occurred in Central Italy during the 2016 Amatrice-Visso-Norcia (AVN) seismic sequence (Chiaraluce et al., 2017), and located through the global approach implemented in the NonLinloc code (Lomax et al, 2000, see Data and Resources). The AVN sequence, recorded by Italian National Seismic Network (Rete Sismica Nazionale, RSN) (Amato and Mele 2008; see Data and Resources) was located by a selection of about 100 stations, deployed in an area of about 100x100 km^2 around the Mw 6.0 Amatrice epicentral area. Earthquakes magnitude in Catalog-1 ranges from 0.1 to 6.5. As another example, Catalog-2 is, instead, a 3-year long subset (2013-2015) of the Italian Seismicity Catalog available in the database ISIDe (ISIDe Working Group, 2016; see Data and Resources). It consists of 68,151 earthquakes located through the linearized approach implemented in the IpoP code (Basili et al., 1984, Amato and Mele, 2008). Catalog-2 includes both crustal and lithospheric earthquakes (down to 600 km) occurred on the entire Italian peninsula (about 1200x1200 km^2 area), located by the whole Italian National Seismic Network (RSN) (about 350 stations), and the magnitude ranges from 0.0 to 5.1. It is worth noting that in the selected period no relevant seismic sequence occurred. Some practical locations details for both catalogs analyzed in this study, can be found in the electronic supplement.

The data adopted for quantifying the q_f factor are the uncertainty estimators associated with the locations of events pertaining to the two catalogs. While in the case of Catalog-1 the whole set of estimators defined in the equation 1 has been used, the location method adopted for the Catalog-2 provides just RMS, NPHS, GAP, ERH and ERZ estimators. Thus, in the latter case, N_{est} in equation 1 is equal to 5.

The distributions of the uncertainty estimators can be grouped in a matrix (Figure 1). We observe that the estimators are correlated with each other, implying a possible bias in the classical approaches for evaluating the quality of an earthquake location by simple threshold. For instance, the selection of a threshold for the RMS estimator, could include events with good quality (e.g., high NPHS and small GAP) but also events, characterized by poor quality (e.g., low NPHS and/or large GAP). This dependence, which is very clear for the Catalog-1 (Figure 1a), could imply that a solution, although well constrained by the majority of estimators, may be downgraded by the presence of a single out-of-goodness-range estimator. The same correlation, although weaker, is also evident for the Catalog-2 (Figure 1b).

Results

We estimated the quality factor for the Catalog-1 and the Catalog-2 (Figure 2 and Figure 3). In both the figures, the locations are divided by the quality class they belong (A-class; B-class; C-class, and D-class). The events identified as outliers by the Chauvenet criterion are the 0.60% and 0.22% for the Catalog-1 and Catlog-2, respectively.

We observe that the shape of epicenters distribution in map-view seems to be independent on the class (Figure 2). On the other hand, when we focus on cross-sections, locations clearly appear more and more diffuse moving from A- to D-class. The cross-sections depicted in Figure 2, have been centered on the main shocks of the sequence and oriented according to the average strike of fault plane responsible of the shocks (Chiaraluce et al., 2017). Therefore, we can compare the seismicity distribution, grouped by classes, to the main tectonic features identified in the area (Michele et al., 2016). We observe that the A-and B-class seismicity are well clustered around the faults responsible for the Amatrice earthquake (section 1), the Norcia earthquake (section 2) and the Visso earthquake (section 3). Alignments of seismicity are well defined in A-class, becoming less clear in the B-class. This effect could be likely ascribed to both the quality of locations and the larger number populating the B-class. In section 2, A- and B-class locations enable good definition of the geometry of the 8-10 km deep seismicity horizon, previously discussed in other studies (Michele et al., 2016; Chiaraluce et al., 2017; Improta et al., 2019). On the other hand, although the C-class seismicity distribution shows the same structures, nevertheless it provides poorly defined geometries. Finally, D-class events distribution seems not to recognize any structures. For practice, it is important that, if locations are only D-class, interpretations should not be made at all.

For the Catalog-2, map-view represents the seismicity distribution, divided by quality class, for the whole Italian peninsula, while cross-sections show hypocenters located along the Calabrian Arc subduction zone (Figure 3). It is worth noting that we are focusing on an area characterized by very complex and non-uniform source-receivers geometry, since the Italian National Seismic Network is only deployed on land, making difficult to constrain locations for off-shore earthquakes. In spite of this, the use of q_f allows to discriminate between main structures. In particular, A- and B-class cross-sections enhance both the crustal and the subduction slab seismicity whereas the more diffused C- and D-class events depict to less defined structures.

In order to further demonstrate the usefulness of q_f factor for the A-D classification, we investigated the statistically distribution of the individual uncertainty estimators for the four classes (Figure S1 in the

electronic supplement). Based on these distributions, we derived the so-called Median Absolute Deviation (MAD) of the different uncertainty estimator distributions for Catalog-1 and Catalog-2. The MAD value is represented as function of the q_f factor (Figure 4) and it is provided in table 1. We note that, independently on the catalog-type, the majority of the estimators show an increasing MAD moving from A- to D-class, confirming that best classes correspond to narrower distributions. On the contrary, the NPHS estimator distribution shows an opposite trend, due to the intrinsic behavior of this estimator.

Discussion and Conclusions

We demonstrated an empirical criterion to describe the quality of seismic locations, by combining uncertainty estimators provided by earthquake location codes. In order to discuss the performance of our approach, we present two different case studies in Italy, concerning different scale seismicity and location methods. In particular, we present both an optimal case, meaning local, dense and homogeneous distribution of earthquakes and recording stations, and a more demanding case, characterized by a 3-year long, diffuse, “no-sequence” distribution of earthquakes occurred along the whole Italian peninsula.

We demonstrate that the combination of different uncertainty estimators allows us to obtain a robust estimation of the location quality. The application to both the catalogs reveals the efficiency of the q_f classification, highlighting higher performances in the case of catalogs of seismic sequences characterized by high density of earthquake-station geometry and limited time duration. However, we show that the q_f classification can be also successfully applied to long-term catalogs for regional areas.

We note that the current definition of the q_f parameter is somewhat dependent on the normalization step of uncertainty estimators. However, when the criterion is applied to a long-in-time catalog, we expect that increasing the duration of the catalog, the uncertainty estimator distributions become more stable and then the normalization factors reach steady values.

The q_f parameter seems to be useful, quick and simple, providing a user-friendly classification of location quality. Moreover, it could represent a powerful instrument, during routine monitoring location procedure, to enhance tectonic features or, for instance, to compute focal mechanisms limiting the analysis just to the best quality classes. We clearly observe that trying to make tectonic interpretations, based on only D-class locations, could imply quite confusing results.

Data and Resources

Earthquake locations for the Catalog-1 are available as supplement to the paper by Chiaraluce et al. (2017). Earthquake locations for Catalog-2 are available in the database ISIDe (Italian Seismological Instrumental and parametric Data-base). In the supplement we describe locations details for the catalogs used and we report statistical distributions of uncertainty estimators.
Figures have been generated by the Generic Mapping Tools (GMT, Wessel and Smith, 1991).

NonLinoc code's details can be found on alomax.free.fr/nlloc.

Details about the Italian National Seismic Network can be retrieved on terremoti.ingv.it/en/instruments.

The Iside database reference is cnt.rm.ingv.it/iside.

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Tables

Table 1. Catalogs location parameters. Number of events and related percentage and Median Absolute Deviation (MAD) for the uncertainty parameters are reported for both catalogs and each quality class.

Catalog	**Num. events** *	**Class** **	**RMS-MAD (s)** ***	**NPHS-MAD** †	**GAP-MAD (°)** ††	**ERH-MAD (km)** †††	**ERZ-MAD (km)** ‡	**LOCDIST-MAD (km)** ‡‡	**PDFRAD-MAD (km)** ‡‡‡
1	4480 (13.7%)	A	0.017	5	7.48	0.08	0.33	0.04	0.09
1	18113 (55.3%)	B	0.020	4	13.64	0.15	0.57	0.08	0.14
1	6898 (21.0%)	C	0.022	2	19.19	0.33	1.00	0.17	0.23
1	3282 (10.0%)	D	0.030	1	29.09	0.93	1.94	0.51	0.42
2	6628 (9.7%)	A	0.040	7	11.00	0.07	0.09	-	-
2	31513 (46.2%)	B	0.050	3	20.00	0.17	0.27	-	-
2	21199 (31.1%)	C	0.060	1	26.00	0.26	0.38	-	-
2	8811 (12.9%)	D	0.070	0	34.00	0.44	0.50	-	-

* Number of events

** Quality class

*** Median Absolute Deviation of Root Mean Square distribution

† Median Absolute Deviation of Number of phases

†† Median Absolute Deviation of Azimuthal Gap distribution

††† Median Absolute Deviation of Horizontal Error distribution

‡ Median Absolute Deviation of Vertical Error distribution

‡‡ Median Absolute Deviation of Location Distance distribution

‡‡‡ Median Absolute Deviation of PDF Radius distribution

Table 1 sums up the results obtained by the above described analysis in terms of number of events separated by quality class and of the Median Absolute Deviation computed for each uncertainty estimator distribution.

List of Figure Captions

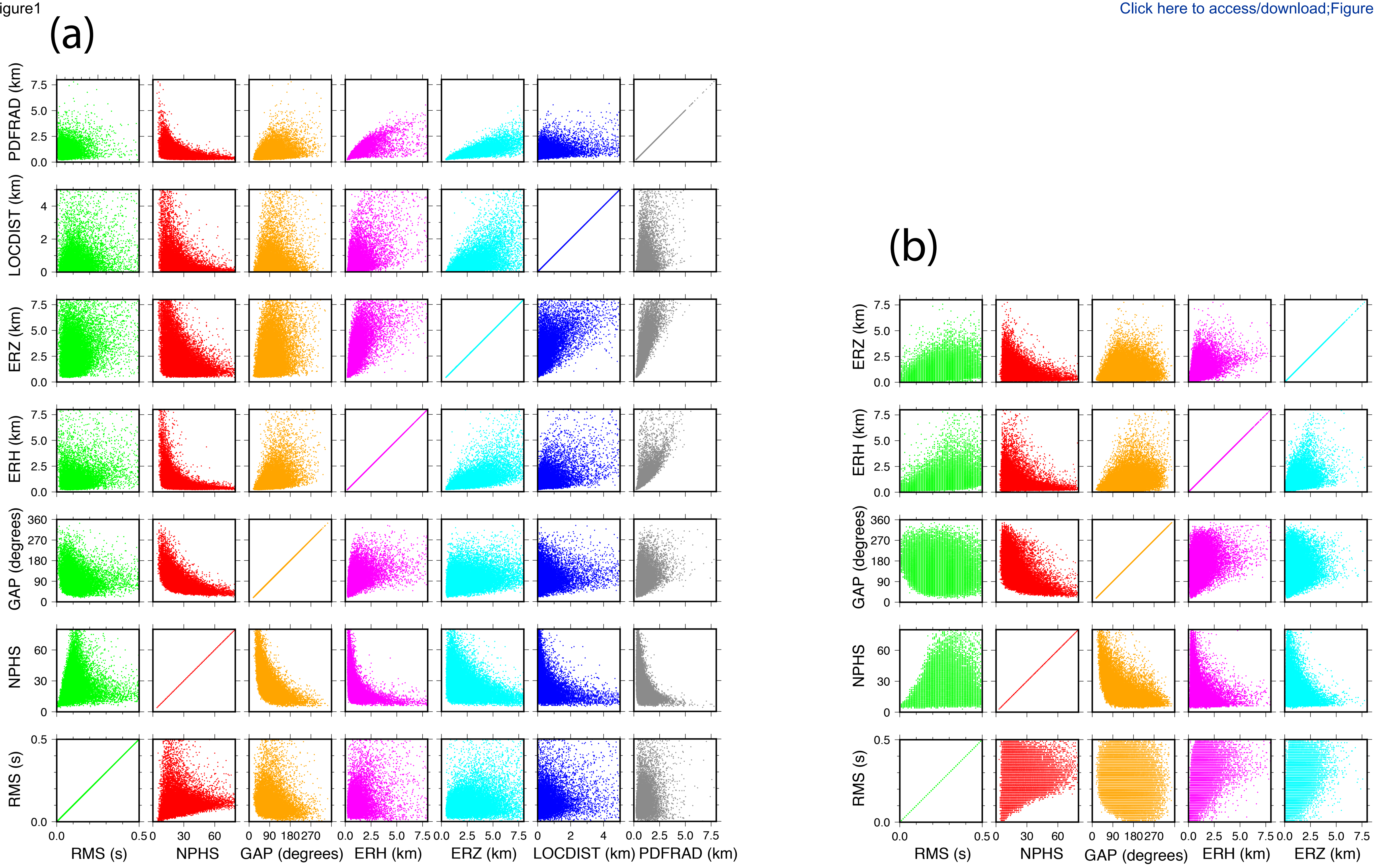
Figure 1. Correlation matrix of the uncertainty estimators. Represented estimators are: the root mean square error (RMS), the number of phases (NPHS), the azimuthal gap (GAP), the errors on the horizontal (ERH) and vertical (ERZ) hypocentral location, the distance between the pdf expected value and its maximum likelihood (LOCDIST) and the radius of the volume described by the scatter points (PDFRAD). The last two estimators are only available for probabilistic location approaches. (a) Catalog-1, produced with the probabilistic approach. (b) Catalog-2, produced with the linearized approach.

Figure 2. Map-view and cross-sections for the Catalog-1 locations, distinct by the quality class. Starting from left, the first, the second, the third and the fourth panel are the A-, B-, C- and D-class locations, respectively. The stars correspond to the Mw >= 5.9 earthquakes occurred during the 2016 Central Italy seismic sequence. Related focal mechanisms are reported both in map-view and at depth. Cross-sections positions correspond to the profiles N60E reported in map-view with the dashed lines. Along them, the +/-2.5 km seismicity is projected. Thick lines in A-class cross-sections underline the main faults according to the study by Chiaraluce et al. (2017). Number of pertaining earthquake locations is reported on the top right of each section~~s~~.

Figure 3. Same as Figure 2 but for the Catalog-2 locations. Cross-section position corresponds to the profile N115E, reported in map-view with the dashed line~~s~~, which crosses the Calabrian arc subduction zone. Along it, the +/-50 km seismicity is projected. Number of pertaining earthquake locations is reported on the bottom left of each section.

Figure 4. Median Absolute Deviation (MAD) as function of quality class (see also Figure S1 in the electronic supplement). Filled dots correspond to the Catalog-1 case study, empty squares to the Catalog-2.

Figure1


(a)
PDFRAD (km)
LOCDIST (km)
ERZ (km)
ERH (km)
GAP (degrees)
NPHS
RMS (s)
0.0
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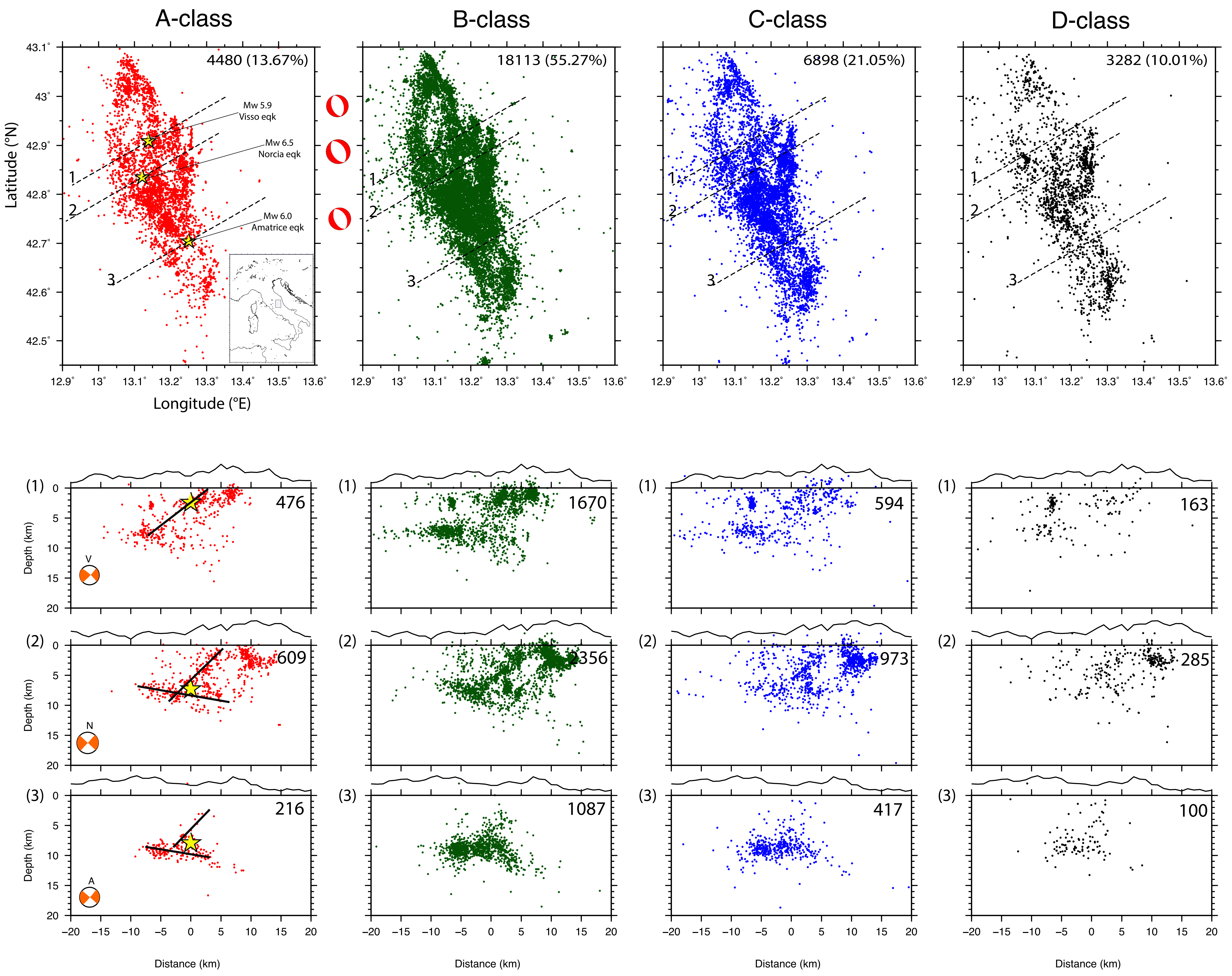
90
180
270
360
0
30
60
0.5
RMS (s)
NPHS
GAP (degrees)
ERH (km)
ERZ (km)
LOCDIST (km)
PDFRAD (km)
(b)
ERZ (km)
ERH (km)
GAP (degrees)
NPHS
RMS (s)
RMS (s)
NPHS
GAP (degrees)
ERH (km)
ERZ (km)

Figure2


A-class
B-class
C-class
D-class
4480 (13.67%)
18113 (55.27%)
6898 (21.05%)
3282 (10.01%)
Mw 5.9
Visso eqk
Mw 6.5
Norcia eqk
Mw 6.0
Amatrice eqk
Latitude (°N)
Longitude (°E)
43.1°
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42.9°
42.8°
42.7°
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12.9°
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13.1°
13.2°
13.3°
13.4°
13.5°
13.6°
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973
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1087
417
100
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Distance (km)
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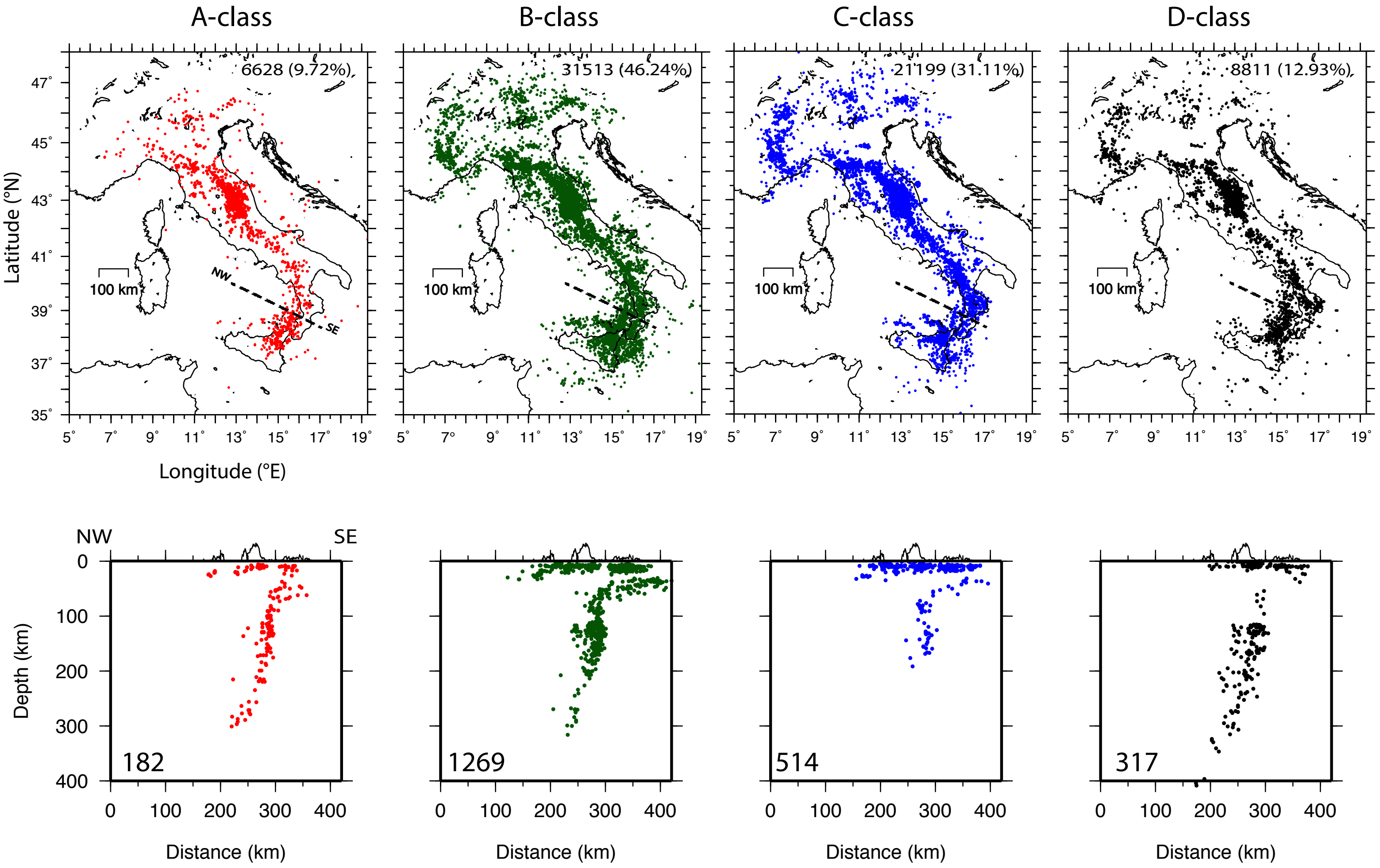
A-class
B-class
C-class
D-class
6628 (9.72%)
31513 (46.24%)
21199 (31.11%)
8811 (12.93%)
Latitude (°N)
47°
45°
43°
41°
39°
37°
35°
5°
7°
9°
11°
13°
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17°
19°
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200
300
400
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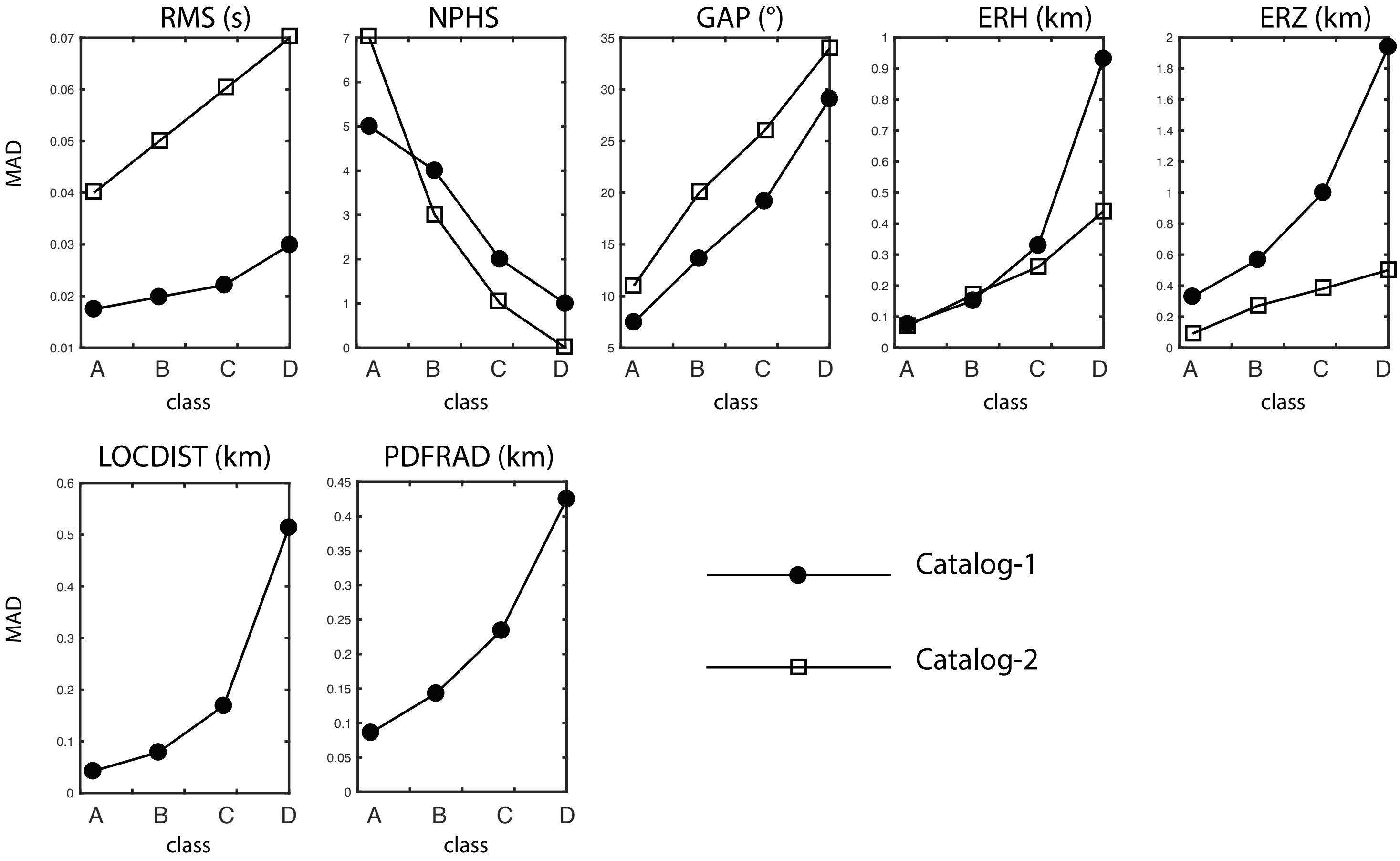
1269
514
317
Distance (km)


RMS (s)
NPHS
GAP (°)
ERH (km)
ERZ (km)
LOCDIST (km)
PDFRAD (km)
MAD
MAD
class
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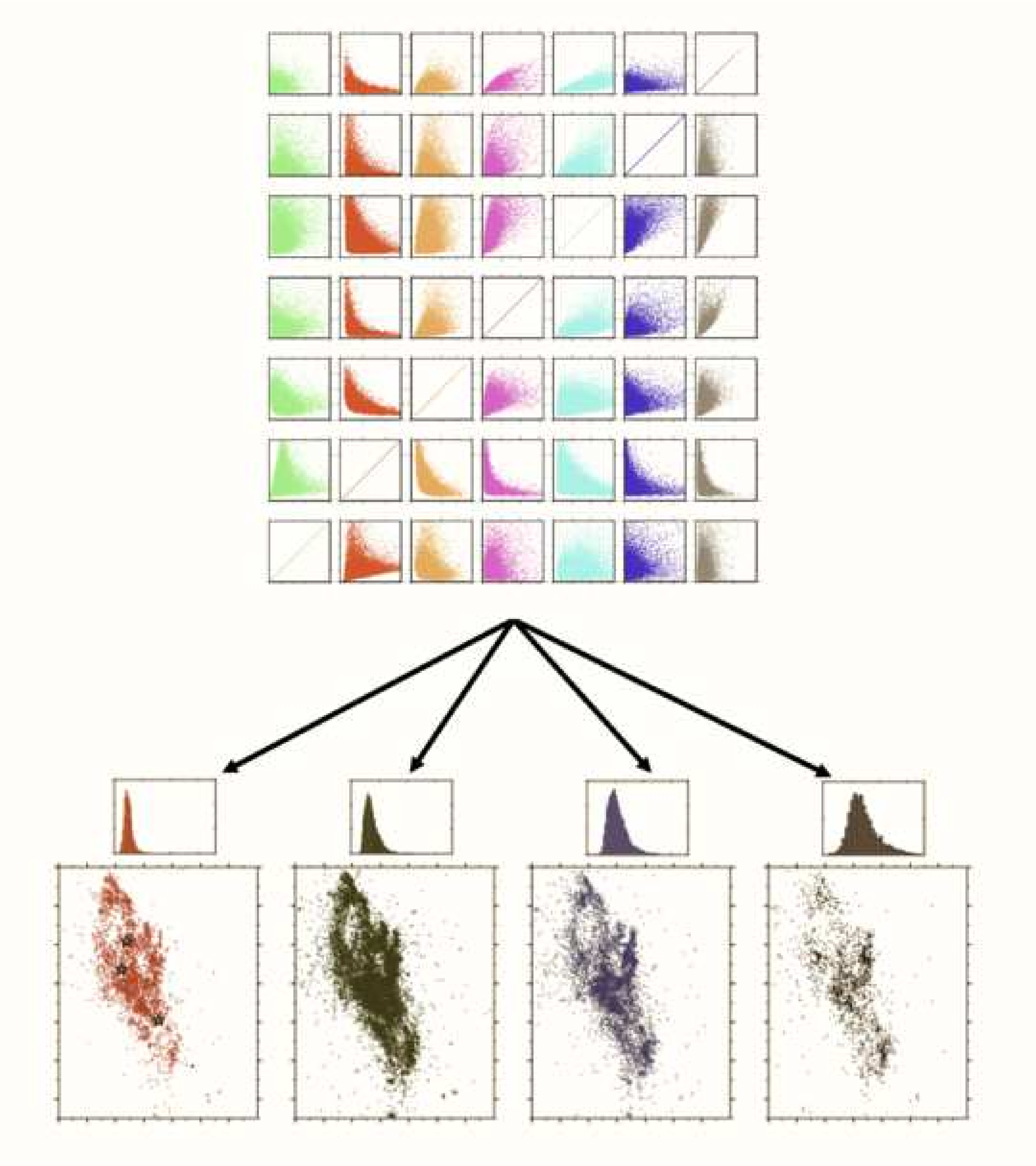
0.3
0.35
0.4
0.45
Catalog-1
Catalog-2



Electronic Supplement to

An Empirical Formula to Classify the Quality of Earthquake Locations

by M. Michele, D. Latorre and A. Emolo

In this supplement we describe locations details for the catalogs used and we report statistical distributions of uncertainty estimators.

Practical locations details

Catalog-1 consists of earthquakes occurred during the first 3 months of the 2016-2017 Central Italy seismic sequence, available in the supplementary material of Chiaraluce et al., (2017). Seismic events were detected by the National Seismic Network (RSN) managed by the National Institute of Geophysics and Volcanology (INGV) by inverting P- and S-wave arrival times hand-picked by the seismologists on duty in the seismic monitoring room and then located by means of the global search approach implemented in the NonLinLoc code (Lomax et al., 2009).

The velocity model used for the location procedure is a gradient version of the layered 1D P- and S-wave velocity model estimated for the region by Carannante et al., (2013). Stations corrections have been used. The Vp/Vs ratio was fixed to 1.86, only for earthquakes with magnitude larger than 5.0. After the location procedure, a cleaning process has been adopted for the Mw < 4.0 events, selecting those with horizontal errors $\leq$ 0.5 km, vertical error $\leq$ 1.5km, RMS $\leq$ 0.3s, and azimuthal gap $\leq$ 120°.

Catalog-2 is a 3-year long subset of the Italian Seismicity Catalog available in the database ISIDe (ISIDe Working Group, 2016; see Data and Resources), covering the period from 2013 to 2015. Earthquakes were located by the INGV (Istituto Nazionale di Geofisica e Vulcanologia) analysts through the linearized approach implemented in the IpoP code (Basili et al., 1984, Amato and Mele, 2008).

In the location procedure adopted by the Seismic Italian Bulletin (see Data and Resources) the velocity model is parametrized by 1D horizontal layers that include an upper-crustal layer of 11 km thick and P velocity = 5 km/s, a lower-crustal layer of 27 km thick and P velocity=6.5 km/s, and deeper half-space corresponding to the mantle layer (P velocity = 8.05 km/s). The Vp/Vs ratio was fixed to 1.73. No station corrections are used but the linearized inversion is driven to the convergence by applying different weights as a function of the arrival time picks accuracy, the residuals between observed and computed travel times, and the distance of the stations from the hypocenter. Finally, after location, no cleaning process has been applied to the catalog and all the located earthquakes during the period 2013-2015 were considered for our study.

Statistical distributions of the uncertainty estimators

Moreover, in order to show the efficiency of the q_f criterion application, we represent in Figure S1 the statistical distributions of the uncertainty estimators included in the q_f computation. To better highlight their behavior, here we illustrated the different statistical distribution, which are clearly narrower in correspondence of best classes. A different trend is recognizable for the NPHS estimator (see main text).

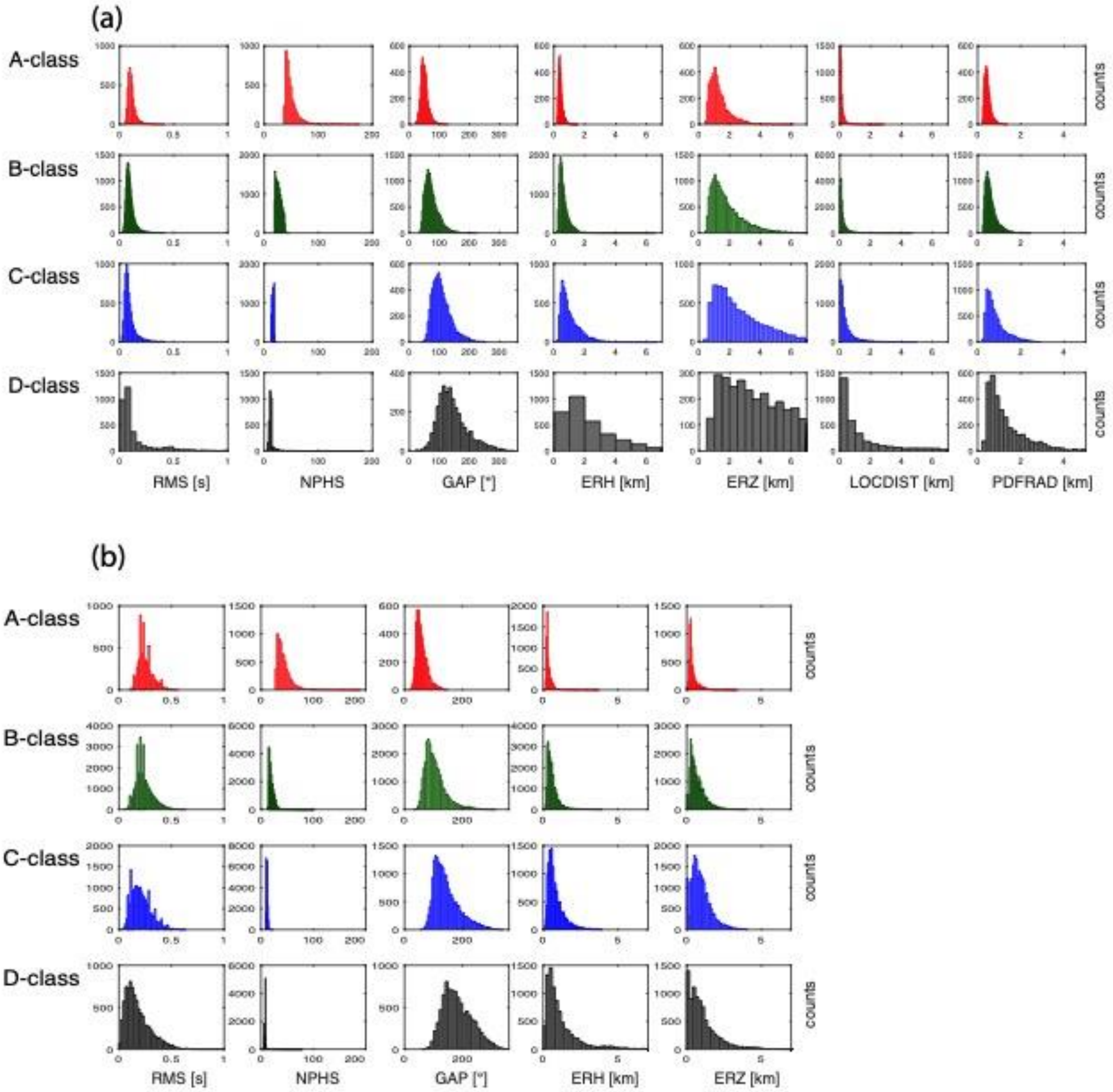


Figure S1. Statistical distribution of uncertainty estimators for Catalog-1, (panel a) and Catalog-2 (panel b). Red, green, blue and black histograms are related to A-, B-, C- and D-class, respectively.

Data and Resources

Earthquake locations for the Catalog-1 are available as supplement to the paper by Chiaraluce et al. (2017). Earthquake locations for Catalog-2 are available in the database ISIDe (Italian Seismological Instrumental and parametric Data-base).

The Iside database reference is cnt.rm.ingv.it/iside.

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