Appendix E

The BOXER method applied to the determination of earthquake parameters from macroseismic data - Verification of the calibration of historical earthquakes in the Earthquake Catalogue of Switzerland (ECOS2009)

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Internal report
Swiss Seismological Service, ETH Zürich
(December 2009)

1. Introduction

The Boxer method (Gasperini et al., 1999) is applied to estimate earthquake locations and magnitudes from macroseismic data collected for historical events in Switzerland. In a first step the method is calibrated with a selected dataset for which macroseimic data and moment magnitudes are available. Dr. Antonio Gómez Capera from INGV Milano supported the Swiss team in derivation of the coefficient for the Boxer method. The performance of this calibration is then validated by application to the same dataset. In a second step alternative calibration parameters derived for the Boxer method are applied to the same dataset. One of these calibrations was derived from a selected dataset of Swiss events during the NERIES project (Gomez Capera et al., 2009). Other calibrations were derived from Italian data during different research projects. From the suite of possible calibration methods, a selection was then applied to assess macroseismic location and magnitude of historical events. The locations and magnitudes of these events can be used to validate a calibration procedure that was developed and applied for the revision of the earthquake catalogue of Switzerland (ECOS-09), and is based on a modified Bakun approach.

2. Methodology: software

Gasperini et al. (1999) proposed a method and software package that uses macroseismic intensity data to assess earthquake parameters including location, magnitude and source dimension. The macroseismic epicenter is estimated based on the definition of a barycenter of the region of largest earthquake effects. The algorithm to estimate the macroseismic location first groups all intensity data points (*IDPs*) into intensity classes and uses the observations in the highest intensity class if a sufficient number of IDPs are available. The epicenter corresponds to a 25% trimmed average (the average of all values included in the interval between the first and third inter-quartiles of the coordinates of all selected localities).
The macroseismic magnitude is computed through a mixed approach combining the assessment of magnitude as a function of epicentral intensity, and as function of the isoseismal areas. This requires two types of calibration functions, one that estimates the magnitude from epicentral intensity, and those that relate magnitude to the area estimated from the mean radius of each intensity class. In order to define the functions, a calibration dataset is needed in order to perform a region-specific regression. The regression method that is used in the software was proposed by Sibol et al. (1987).
Once the calibration functions are defined, historical earthquakes can be analyzed by first computing the distance between the estimated macroseismic epicenter and each IDP. A mean radius for each intensity class can then be determined. M_w is derived from the area of each intensity class. The final magnitude is estimated by combining the magnitude estimates from each intensity class, by also assessing the completeness of intensities in each class, or by selection of the magnitude derived from epicentral intensity. Further details can be found in Gasperini et al. (1999).

3. Calibration dataset

The calibration dataset consists of events located in Switzerland and border areas, which have a reliable location, moment magnitude and good intensity field. These are larger events of the 20th century with high quality macroseismic fields. Selection criteria are the number of IDPs and quality of moment magnitude reported. The magnitudes are instrumentally determined moment magnitudes from European seismic stations according to the following:

- Bernardi et al. (2005) for the events before 1999;
- Braunmiller et al. (2005) for the events before 1999 that are not assessed by Bernardi et al., (2005);
- SED Mw determination since 1999;

The calibration dataset is given in Table 1. This dataset is first used to derive the calibration coefficients for the Boxer method. This calibration dataset contains 38 events with magnitudes ranging between 3.3 and 5.8. IDPs with values smaller or equal to intensity 2 have been removed from the macroseismic data because they are never complete. The macroseismic data of the calibration dataset was put together in early 2009. Since IDPs of some events were revised during the course of the project ECOS-09, there might be changes when compared to the macroseismic data published on the internet.

4. Calibration: procedures and results

The macroseismic location estimation does not require regional calibration. The calibration of the magnitude has been carried out following the guidelines provided in the tutorial of the software (Gasperini, 2004, 2008). To find an optimum estimation of the macroseismic parameters, different calibration exercises have been performed:

a) using subsets of the dataset according to defined magnitude ranges of the events;
b) using subsets of the macroseismic data: only the upper three intensity classes or all intensity classes.

The Boxer program allows a calibration using the following functional form:

$$M_i = a + bLog^2\left(A_i\right) + cI_0^2 \qquad (1)$$

where *a, b and c* are empirical parameters, I_0 the epicentral intensity and A_i the isoseismal area for the i-th class of intensity observations, which is defined by:

$$A_i = \pi R_i^2 \qquad (2)$$

R_i (in km) is the average epicentral distance of all localities of the i-th intensity class.

The magnitude of the earthquake is computed as the trimmed mean. The estimated moment magnitude, hereafter named as *BxMw,* is computed for each earthquake as:

1) the weighted average of the values estimated for each intensity class,
2) the median of the values estimated for each intensity class,
3) a magnitude for each intensity class in order to assign magnitude to an event using completeness information and historical knowledge.

The two different weighting schemes in 1) and 2) are described in the user guide (Gasperini, 2004) and the tutorial for the calibration procedure (Gasperini, 2008). The uncertainty of the resulting magnitude is given by the inverse of the square root of the sum of weights. In 3) the user may also select the intensity degrees for which the calibration is calculated.

If only integer values are listed, the intermediate intensities are rounded down to the lower integer intensity. Intensities for which the calibration failed (typically due to too few IDPs) are not used for magnitude determination. In the cases where the data are insufficient to apply the above method, the macroseismic magnitude is estimated from the epicentral intensity according to the following relation:

$$M = a + bI_0 \qquad (3)$$

The Boxer method can generally only be applied within the range of magnitudes of the calibration dataset.

event_no	YEAR	MONTH	DAY	HOUR	MINUTE	catalog02_Mw	Mw(bestmag)
814	1905	4	29	1	59	5.7	5.1
239	1905	12	25	17	5	4.8	4.7
891	1911	11	16	21	25	5.8	5.5
945	1915	8	25	2	15	4.9	4.6
947	1924	4	15	12	50	5.5	5.2
960	1925	1	8	2	45	5	4.8
1039	1935	6	27	17	19	5.7	5.6
20009	1946	1	25	17	32	6.1	5.8
20007	1946	5	30	3	41	6	5.5
1058	1954	5	19	9	35	5.4	5.3
1060	1960	3	23	23	10	5.3	5
1061	1964	2	17	12	20	5	4.8
1157	1964	3	14	2	39	5.7	5.3
1068	1968	8	19	0	36	5.2	4.7
1071	1971	9	29	7	18	5.1	4.9
1086	1978	9	3	5	8	5.15	5.5
1090	1980	7	15	12	17	4.9	4.8
1098	1991	11	20	1	54	4.6	4.7
1108	1994	12	14	8	56	4.26	4.3
1102	1996	7	15	0	13	4.59	4.6
10180	1997	11	22	4	56	3.62	3.6
10220	1999	2	14	5	57	4	4
10240	1999	12	29	20	42	4.9	4.9
311	2001	2	23	22	19	3.55	3.4
1782	2002	4	29	15	14	3.5	3.5
50973	2003	3	22	13	36	3.8	3.9
50977	2003	4	29	4	55	3.5	3.4
50980	2003	5	6	21	59	3.7	3.6
51030	2003	7	17	2	27	3.6	3.5
51039	2003	7	18	11	1	3.6	3.5
51051	2003	8	1	3	20	3.7	3.7
51075	2003	8	22	9	21	3.7	3.6
51077	2003	8	22	9	30	3.5	3.5
51260	2004	6	21	23	10	3.6	3.3
51278	2004	6	28	23	42	3.8	3.4
51355	2004	12	5	1	52	4.9	4.5
51437	2005	5	12	1	38	3.9	3.7
54351	2008	1	21	16	40	3.8	3.7

Table 1. Calibration dataset used to calibrate the functions in the Boxer code. Catalog02_Mw is the moment magnitude published in the earthquake catalogue of Switzerland (ECOS-02), "Mw(bestmag)" corresponds to the moment magnitude in the calibration dataset as described in chapter 3.

4.1. Results of the calibration

Within the calibration exercise, we addressed the following questions:

a) What is the influence of the use of the different intensity classes or ranges of intensity classes?
b) Do we obtain differences in results when using a subset of calibration events in different magnitude ranges?
c) Can we apply other calibration coefficients to the Swiss data?

The calibrated coefficients for Boxer, obtained from subsets of calibration events, are provided in the following tables (named as calibrated coefficients *ECOS09*). The results are computed using only those events that provided a reliable epicenter location not further than 20km away from the known catalogue location.
The three sets of calibrated coefficients correspond to the three exercises performed with the following data:

- *Using the entire calibration dataset (Table 2).*
- *Using events from the calibration dataset with magnitudes smaller or equal to 4.2 (Table 3).*
- *Using events from the calibration dataset with magnitudes larger than 4.0 (Table 4).*

We note that we can compute calibration coefficients only up to intensity 7. Larger events with intensities greater than 7 can therefore not be satisfactorily assessed (e.g. larger than the 1946 Mw=5.8 event).

Boxer								
Intensity	**Coeff. a**	**Coeff. B**	**Coeff. C**	**st. dev. of regr.**	**weight norm. factor**	**deg. of freedom of regr.**	**a coeff. x M-lo eq.**	**b coeff. x M-lo eq.**
3.0	2.93087	0.07585	0.0000	1.2643	81.2759	27	7.012	-0.330
4.0	3.48752	0.04835	0.0000	1.5648	123.0690	27		
5.0	3.53656	0.08198	0.0000	1.3730	101.2105	17		
6.0	4.35668	0.06569	0.0000	0.8644	35.8182	9		
7.0	1.83757	0.26421	0.0000	2.7282	24.0000	2		

Table 2. Calibrated coefficients obtained with entire calibration dataset (mis-located events have been removed).

Boxer									
	Intensity	**Coeff. a**	**Coeff. B**	**Coeff. C**	**st. dev. of regr.**	**weight norm. factor**	**deg. of freedom of regr.**	**a coeff. x M-lo eq.**	**b coeff. x M-lo eq.**
CH	3.0	3.59359	-0.00988	0.0000	0.1494	42.5833	10	0.0	0.0
	4.0	3.73488	-0.02649	0.0000	0.1619	110.0000	7		

Table 3. Calibrated coefficients obtained with events from the calibration dataset with magnitudes smaller or equal to 4.2 (mis-located events have been removed).

Boxer									
	Intensity	Coeff. a	Coeff. B	Coeff. C	st. dev. of regr.	weight norm. factor	deg. of freedom of regr.	a coeff. x M-lo eq.	b coeff. x M-lo eq.
CH	3.0	4.57338	-0.00016	0.0000	1.3840	108.5882	15	7.012	-0.330
	4.0	5.31566	-0.03960	0.0000	1.7437	128.9500	18		
	5.0	3.53656	0.08198	0.0000	1.3730	101.2105	17		
	6.0	4.21828	0.07238	0.0000	0.9034	32.1818	9		
	7.0	1.83757	0.26421	0.0000	2.7282	24.0000	2		

Table 4. Calibrated coefficients obtained from the calibration dataset with magnitudes larger than 4.0 (mis-located events have been removed).

In the validation of the calibration exercise other calibrated coefficients (mainly derived from Italian data) are tested. This included, in a second step, a combination between calibrated coefficients obtained from a Swiss calibration dataset and coefficients obtained from Italian datasets. The following set of original calibrated coefficients have been used for this purpose:

- NA4CH*: coefficients derived in the NERIES NA4 project (Gómez-Capera et al,. 2009), by the Italian partners using a Swiss dataset that corresponds to a subset of events given in Table 1. The coefficients are given in Table 5. The calibrated coefficients for intensity 7 are rather different than the values in Table 2. We therefore suppose that some adjustment has been made to derive these coefficients.*
- NA4IT*: coefficients derived in the NERIES NA4 project (Gómez-Capera et al,. 2009), using an Italian calibration dataset (Table 6).*
- 2004IT: *Italian calibration performed by C. Meletti (see Gómez-Capera et al. (2009) for further information) using an Italian calibration dataset (Table 7).*

Boxer									
	Intensity	Coeff. a	Coeff. B	Coeff. C	st. dev. of regr.	weight norm. factor	deg. of freedom of regr.	a coeff. x M-lo eq.	b coeff. x M-lo eq.
CH	2.0	3.78845	0.04826	0.00000	0.3610	21.8000	8	1.600	0.531
	3.0	3.78522	0.06349	0.00000	0.2764	42.2308	11		
	4.0	3.68597	0.08364	0.00000	0.3413	57.5882	15		
	5.0	4.44374	0.06161	0.00000	0.2007	73.1000	8		
	6.0	4.97757	0.04223	0.00000	0.2751	33.0000	2		
	7.0	3.33181	0.25350	0.00000	0.0000	29.0000	0		

Table 5. NA4CH calibrated coefficients.

Boxer									
	Intensity	Coeff. a	Coeff. B	Coeff. C	st. dev. of regr.	weight norm. factor	deg. of freedom of regr.	a coeff. x M-lo eq.	b coeff. x M-lo eq.
CH	2.0	2.72168	0.06502	0.02294	0.2543	18.5385	10	1.831	0.500
	3.0	2.91254	0.05820	0.02368	0.2919	55.7222	15		
	3.9	25.81147	-0.86902	0.00000	0.0000	7.0000	0		
	4.0	2.66605	0.15810	0.00000	0.2011	88.8889	16		
	5.0	3.72208	0.03952	0.02307	0.2298	73.8125	13		
	6.0	4.29467	0.00505	0.02452	0.1619	120.7143	4		
	7.0	4.45819	0.15915	0.00000	0.2482	117.0000	4		
	8.0	3.66031	0.19864	0.00884	0.0000	86.667	0		
	9.0	5.14999	0.23878	0.00000	0.0000	16.5000	0		

Table 6. NA4IT calibrated coefficients.

Boxer									
	Intensity	Coeff. a	Coeff. B	Coeff. C	st. dev. of regr.	weight norm. factor	deg. of freedom of regr.	a coeff. x M-lo eq.	b coeff. x M-lo eq.
CH	2.0	3.14332	0.06804	0.01442	0.2739	11.4946	90	2.182	0.423
	2.5	3.35407	0.0549	0.01611	0.246	11.9048	60		
	3.0	3.36459	0.05417	0.01698	0.2753	20.739	246		
	3.5	3.44765	0.04915	0.01776	0.2852	18.4626	144		
	3.9	3.31972	0.05977	0.01877	0.2713	10.4848	30		
	4.0	3.32285	0.05977	0.01816	0.2633	25.223	284		
	4.5	3.4039	0.0529	0.02044	0.2876	25.773	138		
	5.0	3.44807	0.07035	0.01695	0.2754	27.6503	180		
	5.5	3.83897	0.06795	0.0134	0.3201	20.4179	64		
	6.0	4.0229	0.0437	0.01714	0.362	30.4457	89		
	6.5	3.89861	0.06143	0.01664	0.3428	25.8333	51		
	7.0	3.96195	0.05068	0.01904	0.3144	42.1273	52		
	7.5	4.50698	0.08161	0.01049	0.2558	30.8077	23		
	8.0	4.66038	0.0843	0.01049	0.1749	40.15	17		
	8.5	5.92602	0.09129	0	0.1973	29.875	6		
	9.0	5.63151	0.14275	0	0.2246	22.625	6		

Table 7. 2004IT calibrated coefficients.

4.2. Validation of the calibration

The performance of the different calibrations is assessed by comparing the estimated macroseismic location and magnitude for all events in the calibration dataset with their original location and M_w shown in Table 1. The following strategies have been tested to estimate the macroseismic parameters for the events in the Swiss calibration dataset:

- **Different calibration datasets used**

  Coefficients obtained from the same calibration dataset

  - Using the coefficients obtained with the calibration dataset *ECOS09* (*cal_ECOS09*).
  - Using the coefficients obtained with the calibration dataset *NA4CH* (*cal_NA4CH*).
  - Using the coefficients obtained with the calibration dataset *NA4IT* (*cal_NA4IT*).
  - Using the coefficients obtained with the calibration dataset *2004IT* (*cal_2004IT*).

  Hybrid procedures in order to extend the range of intensities

  - Complementing the calibrated coefficients of dataset *ECOS09* (highest intensity 7), with the coefficients of intensity 8 and 9, corresponding to the two highest intensity classes from calibration dataset *NA4IT* (*cal_ECOS09_NA4IT*).

  - Complementing the calibrated coefficients of dataset *ECOS09* (highest intensity 7), with the coefficients of intensity 7.5 to 9, corresponding to the highest intensity classes from calibration dataset *2004IT* (*cal_ECOS09_2004IT*).

Once one of the calibration approaches listed above has been chosen, a second aspect of the strategy is defined based on the calibration information used:

- **Intensity information**
  - Using calibrated coefficients obtained for all available intensity classes of the calibration dataset.
  - Using calibrated coefficients for the three highest intensity classes for each event (depending on the event).

In a first step the coefficients in Tables 2, 3 and 4, obtained in the ECOS09 calibration exercise, are implemented and tested, both using all intensities and only the three highest intensity levels. In this case another aspect of the calibration has to be considered: it concerns the different coefficient sets obtained by using subsets of calibration events in different magnitude ranges. In further exercises the rest of the calibration tests listed above are analyzed. The assessments using all these strategies are summarized and discussed here, with most relevant results provided in figures.

4.2.1. Estimation of macroseismic location

The macroseismic location has been assessed for the different calibrated coefficients presented above. The results show that the estimation of location is very robust using the different approaches. There are no significant differences. As an example, Figure 1 and Figure 2 depict the distance residuals between the catalogue location given in Table 1 and the computed macroseismic location for the Swiss calibration dataset, using the calibrated coefficients of *cal_ECOS09*. It can be seen that there are five events that are mis-located by more than 20km. These events were those that were removed for the determination of the final calibrated coefficients for Boxer.

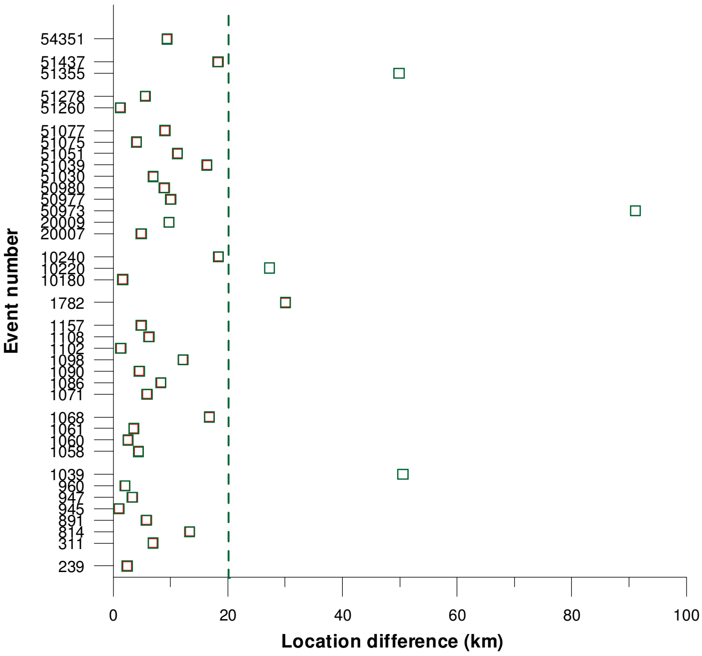


Figure 1. Distance in km between the catalogue (ECOS-02) locations and the macroseismic locations estimated with Boxer for the Swiss calibration dataset (cal_ECOS09). The results from two different procedures are shown: calibration performed with all events, estimation of location with all intensity levels, calibration with all events, estimation of location only taking into account the three highest intensity levels.

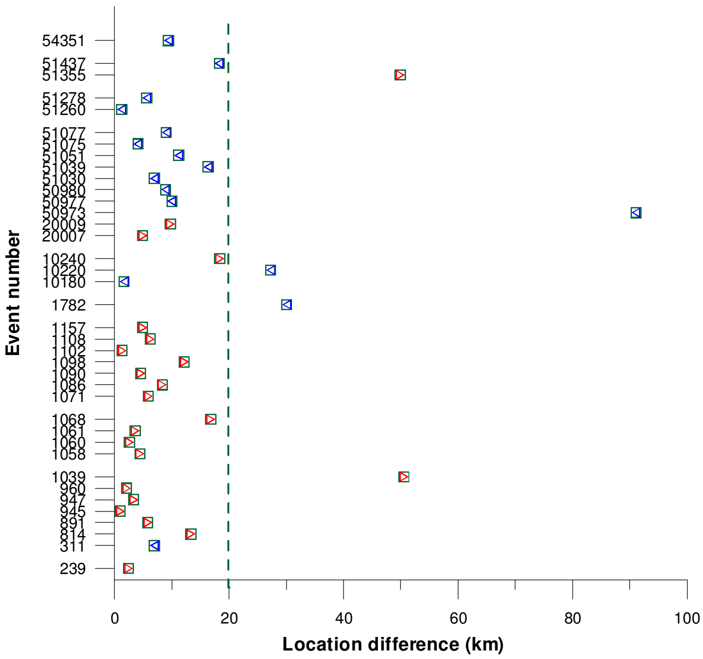
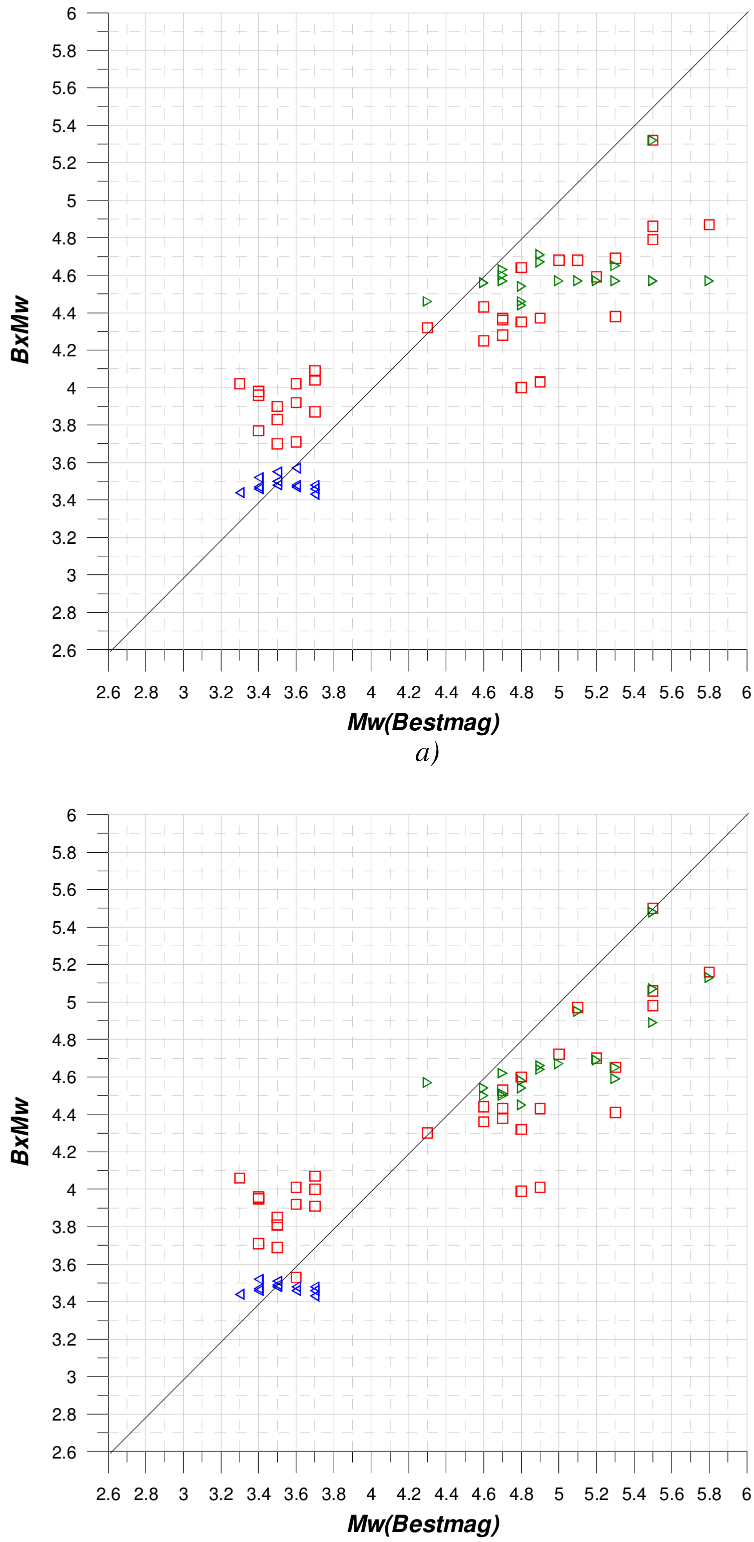


Figure 2. Distance in km between the catalogue (ECOS-02) locations and the macroseismic locations estimated for the Swiss calibration dataset (cal-ECOS09). The results from three different procedures are shown. All results are derived using only the coefficients obtained for the three highest levels of intensity: The calibration is performed with: all events, events with Mw≤*4.2, events with* Mw>*4.0.*

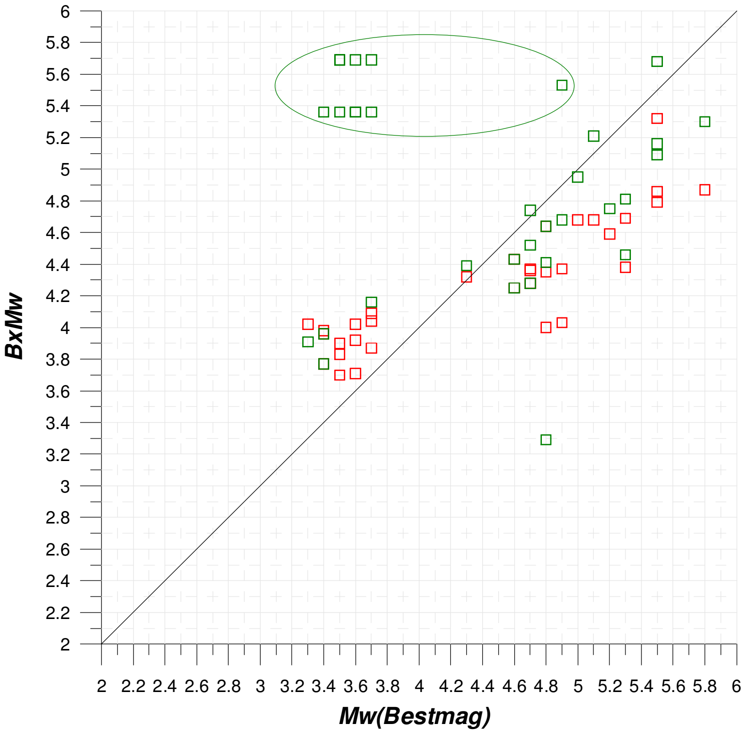
4.2.2. Estimation of macroseismic magnitude

The macroseismic magnitude is computed for the different calibration procedures. Figure 3 illustrates the impact in the assessment of the use of different subsets of calibration events in different magnitude ranges. The M_w(bestmag) in Table 1 is used for comparison. All intensity classes are used. The Boxer coefficients are given in Table 2, 3, and 4. The computed macroseismic magnitude is presented as the median (upper part a) of Figure 3 and the weighted average value derived from the magnitude estimates for all intensity classes (lower part b) of Figure 3. When using all events for the calibration (□) there is a trend to overestimate magnitudes for small magnitudes and underestimate magnitudes for larger events. When using the calibration events in a limited magnitude range, results are improved. The magnitudes of small events are no longer overestimated (◁). For larger events the computed magnitudes are slightly increased (▷). The results for the larger events are still unsatisfactory, which might be caused by incomplete intensity classes.
Figure 4 summarizes the results obtained with the calibration procedures that are based on the use of different intensity classes. The calibrated coefficients given in
Table *2* are used. Results from two different procedures are shown: 1) using calibrated coefficients of all intensity classes (□), and 2) taking only the three highest classes into consideration (□). For events with Mw>4.0, the macroseismic magnitudes are improved when using the highest intensity classes for the estimation of the macroseismic magnitude. A possible explanation is that the three highest intensity classes of an event are more complete than the lower intensity classes.
Results are unacceptable for some events with Mw<=4.2 with macroseismic magnitudes that are much too high (shown within the ellipse in the Figure 4). A common feature of these events is that they have few IDPs, and therefore the computation of a macroseismic magnitude with the radii method is not successful.
We conclude that reliable estimation of macroseismic magnitudes using the three highest intensity classes is only successful for events that have sufficient IDPs in the intensity classes I=5, 6, and 7. Low magnitude events have no information in this intensity range, because the maximum intensity is 4 or lower.
Finally, the influence of both aspects is combined including the range of the magnitude of the calibration events and the intensity classes used. The macroseismic magnitude has been computed for the calibration dataset separately for events with Mw≤4.2 and Mw>4.0. Calibrated coefficients derived from the corresponding subset (see Table 3 and Table 5) are applied, using all intensity classes provided in the tables, and the three highest intensity classes only. Results are given in Figure 5. We can conclude that the calibration procedure should be performed for different magnitude ranges, and that results are better when applying the calibration coefficients corresponding to the three highest intensity levels, mostly due to incomplete macroseismic fields at lower intensity levels. For two events this general conclusion cannot be applied. One of these two events has been discussed before; it is inside the ellipse in Figure 4.

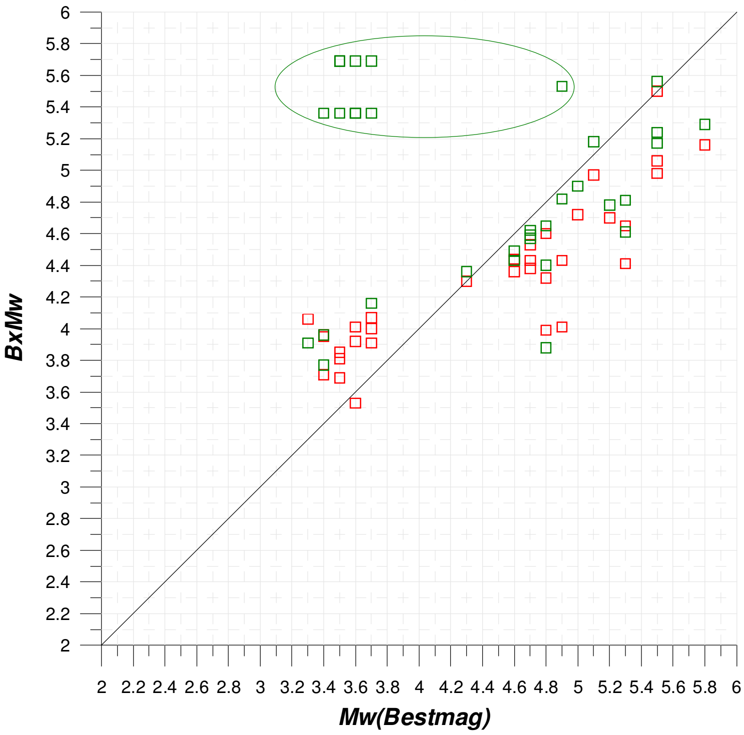


b)

Figure 3. Macroseismic magnitudes computed for the calibration dataset (cal_ECOS09), applying the calibrated coefficients to all intensity classes and: □ calibration coefficients obtained from all events (Table 2); ◁ calibration coefficients obtained from events with Mw≤4.2 (Table 3); ▷ calibration coefficients obtained from events with Mw>4.0 (Table 4). a) Median values; b) weighted averages.

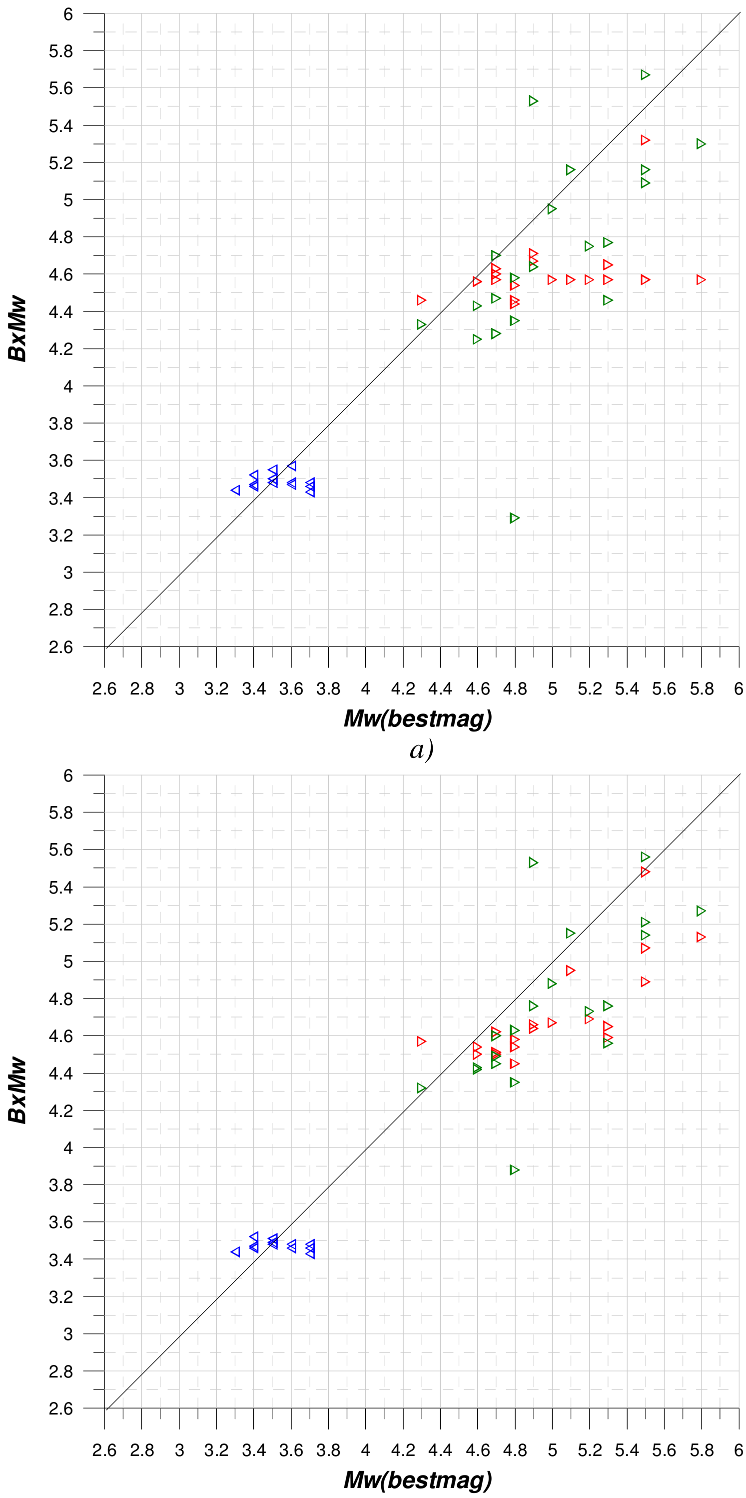


a)



b)

Figure 4. Macroseismic magnitudes computed for the calibration dataset (cal_ECOS09, not taking into account events that are mis-located) using different procedures: □ results obtained with calibrated coefficients derived from all events (Table 1) and all intensity classes, □ results obtained with calibrated coefficients derived from all events (Table 1) but only using the three highest intensity classes. For events inside the ellipse, the method was not successful. a) Median values, b) weighted averages.



a)

b)

Figure 5. Macroseismic magnitudes computed for the calibration dataset (cal_ECOS09) for the calibrated coefficients obtained with the two magnitude ranges (Tables 3 and 4), and different intensity classes: ◁ events with Mw≤4.2, ▷ events with Mw>4.0 and all intensity classes, ▷ events with Mw>4.0 using only the three highest intensity classes. a) Median values, b) weighted averages.

Within the magnitude range of the dataset of historical events, there is a need to assess parameters for earthquakes larger than the events in the calibration dataset. The Swiss calibration dataset does not provide reliable coefficients for the Boxer code above a moment magnitude of about 5.5-6.0. Therefore we now consider calibrated coefficients that should cover earthquakes with magnitudes above this limit (Table 5, 6 and 7). While the coefficients in Table 5 cannot be applied for events above magnitudes of about 6.0, the coefficients in the other tables provide coefficients for larger intensities from Italian data. We focus here on events with Mw larger than 4.0. The original calibrations were presented in section 4.2 (*cal_NA4CH, cal_NA4IT, cal_2004IT).* Hybrid calibrations combine coefficients obtained from different calibration dataset *(cal_ECOS09_NA4IT* and *cal_ECOS09_2004IT).*

All the procedures are now applied to the Swiss calibration dataset given in Table 1. We apply the calibrated coefficients to the three highest intensity levels of each event taking into account the incompleteness of the intensity field at lower intensity levels.

Figure 6 to 10 summarize the results. In each figure one of the proposed calibration procedures is compared to the original procedure *cal_ECOS09*. While the original procedures *cal_NA4CH, cal_NA4IT,* and *cal_2004IT* provide macroseismic magnitudes that are slightly too high, the hybrid calibration procedures *cal_ECOS09_NA4IT* and *cal_ECOS09_2004IT* are very similar and lead to better results. The original calibration *cal_ECOS09* (with the exception of one event) give good results in the magnitude range up to 5.5, however on average the resulting macroseismic magnitudes are slightly too low. At this stage, the calibration procedures *cal_ECOS_2004IT* and *cal_ECOS09_NA4IT* represent rather balanced results (Figure 10) for the magnitude range of the Swiss calibration data. However, the largest event in the calibration dataset, the 1946 Mw=5.8 event, receives only a macroseismic magnitude of 5.4, which needs further consideration. This is addressed in the following chapter. The 1946 event can also not be reliably estimated with the procedure *cal_ECOS09* because intensities of the event exceed the level of intensity 7.

From the comparison of estimated magnitudes for the different intensity classes of one event it becomes evident that the coefficients for the intensity class 7 are not very reliable in the procedure *cal_ECOS09*, most probably due to the limited number of larger events in the calibration dataset. The coefficients in the procedure *cal_NA4CH* were derived using a Swiss dataset that corresponds to a subset of calibration events given in Table 1. The calibration coefficients for intensity 7 are rather different from the values in *cal_ECOS09* and the estimated magnitudes for the intensity class 7 provides reasonable values when compared to those from the other intensity classes. This allows the procedure *cal_NA4CH* to be applied to events with the magnitudes up to about Mw of 6.0.

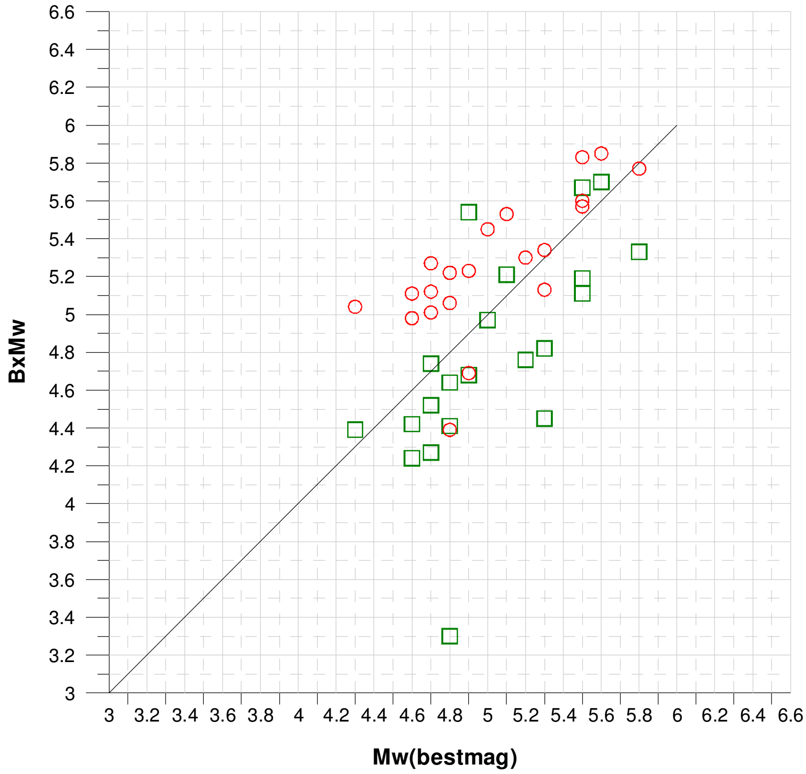


Figure 6. Macroseismic magnitudes (BxMw) for events in the Swiss calibration dataset with Mw>4.0, using only the three highest intensity levels and the following procedures: □ cal_ECOS09, ○ cal_NA4CH, (see 4.1).

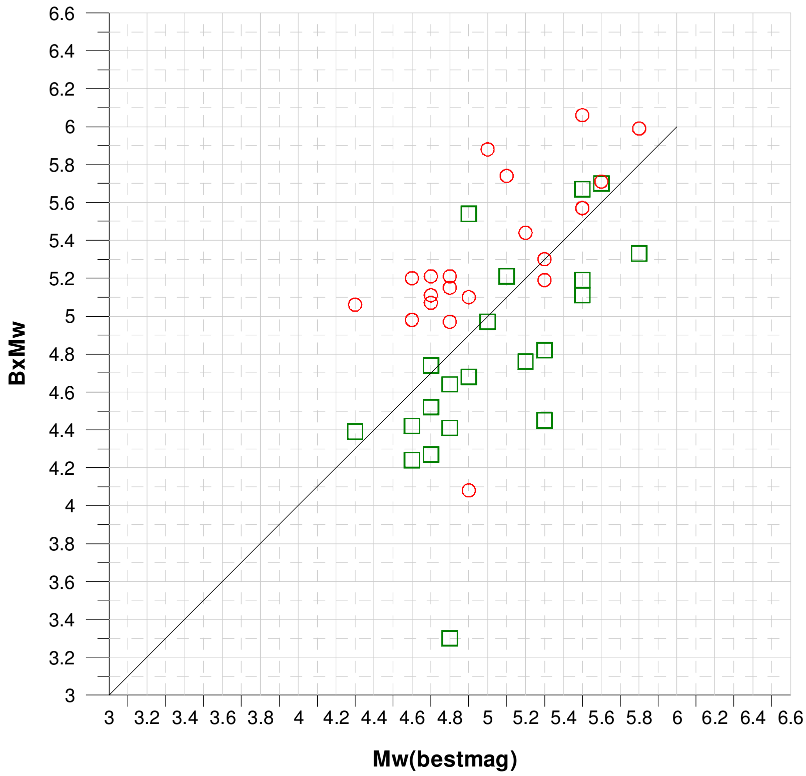


*Figure 7. Macroseismic magnitudes (*BxMw*) for events in the Swiss calibration dataset with Mw>4.0, using only the three highest intensity levels and the following procedures: □ cal_ECOS09, ○ cal_NA4IT, (see 4.1).*

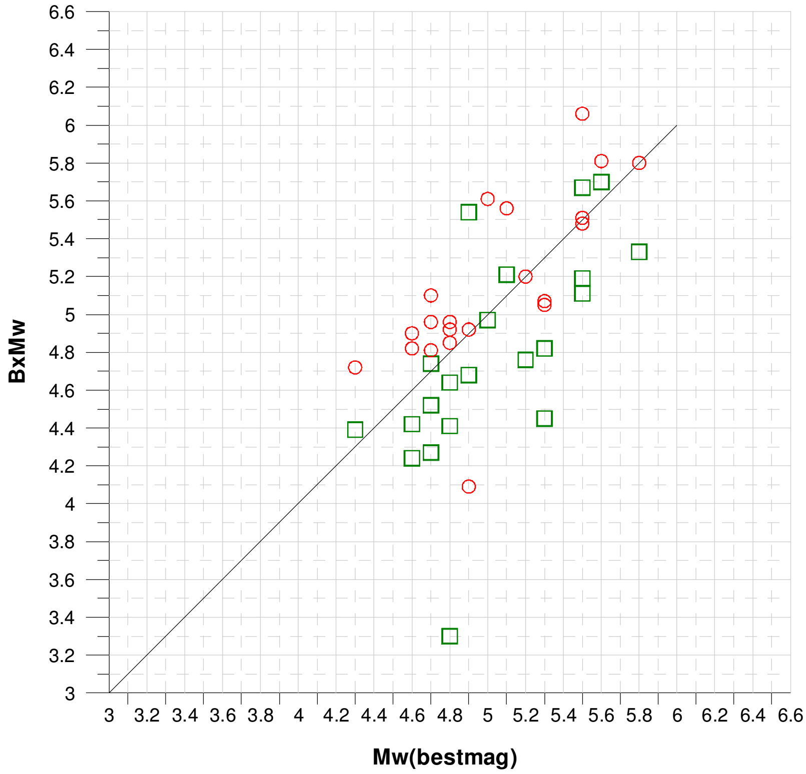


*Figure 8. Macroseismic magnitudes (*BxMw*) for events in the Swiss calibration dataset with Mw>4.0, using only the three highest intensity levels and the following procedures:* □ *cal_ECOS09,* ○ *cal_2004IT, (see 4.1).*

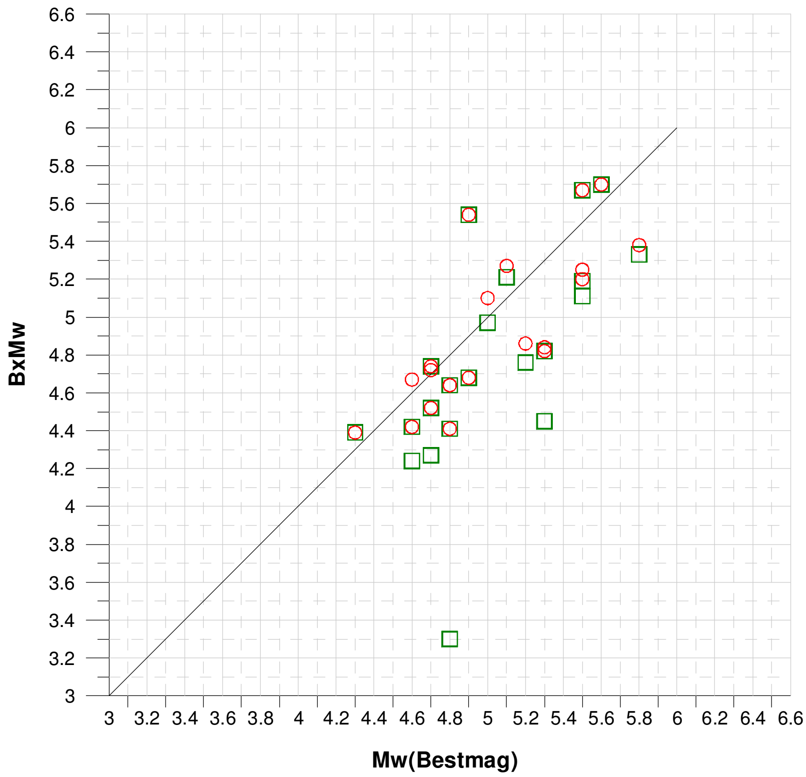


*Figure 9. Macroseismic magnitudes (*BxMw*) for events in the Swiss calibration dataset with Mw>4.0, using only the three highest intensity levels and the following procedures:* □ *cal_ECOS09,* ○ *cal__ECOS09_NA4IT, (see 4.1).*

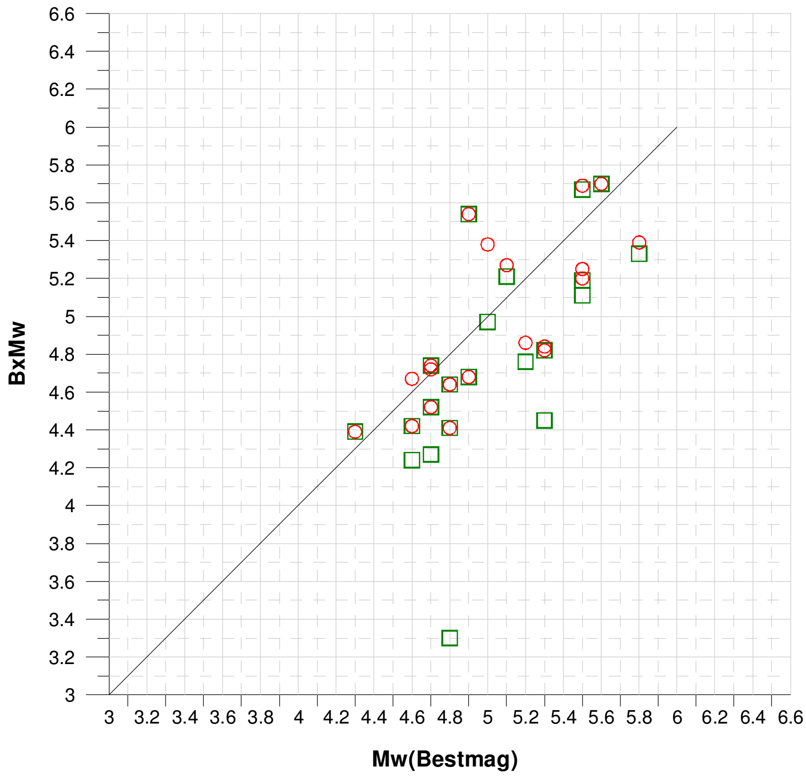


*Figure 10. Macroseismic magnitudes (*BxMw*) for events in the Swiss calibration dataset with Mw>4.0, using only the three highest intensity levels and the following procedures:* □ *cal_ECOS09,* ○ *cal_ECOS09_2004IT, (see 4.1).*

5. Estimation of macroseismic earthquake parameters for historical earthquakes

The calibration exercises that are summarized in the previous chapters have brought light into essential issues regarding calibration of macroseismic data using the Boxer code. The different calibration procedures are now applied to estimate the macroseismic parameters (magnitudes) of some of the larger events in the historical catalogue (see Table 8). We apply the following strategies using the usable highest three intensity classes:

1) *cal_ECOS09* (only for the events with epicentral intensity smaller than 9),
2) *cal_NA4CH* (only for the events with epicentral intensity smaller than 9),
3) *cal_NA4IT,*
4) *cal_2004IT,*
5) *cal_2004IT* using the maximum probable intensities (Imax) for each event (see below),
6) *cal_ECOS09_NA4IT*,
7) *cal_ECOS09_NA4IT* using the maximum probable intensities (Imax) for each event (see below).

We only compute a magnitude from the part of the intensity field, for which we assume, from historical evidence, is complete.

In the case of the Italian calibrated coefficients, it has to be taken into consideration that the macroseismic data used in calibration are usually given in the MCS scale (Sieberg, 1932). Although the Italian database is rather homogeneous for Italy, there may be differences at the border areas (Stucchi et al., 2007). The MCS scale shows differences with the EMS (and MKS) scale, especially in the intensity range between VII and IX. It is also assumed that the practice in Italy is to assign intensities to the highest level for an observation at a specific site. The values in MCS can therefore be up to one intensity unit higher than those expressed in the EMS scale describing the same earthquake effects. However this assumption can presently not be tested.

Since 2000 the Swiss Seismological Service (SED) has been assessing intensity values following the rules defined in the EMS. The analysis is performed by a designated working group. Macroseismic intensity in the EMS-98 scale is assigned by settlement, using all sources of information about effects to buildings and humans within it. Depending on the intensity-relevant content of the reports, the project group assigned a most probable intensity (Iw) and a range defined by the minimum (Imin) and maximum probable intensities (Imax). Because assessment of intensities might differ in Switzerland and Italy, the procedures with cal_2004IT and the hybrid procedure *cal_ECOS09_NA4IT* are therefore not only applied to the most probable intensity values (Iw), but also to the maximum intensities (Imax) for the selected historical event.

Due to the fact that magnitudes of calibration events changed after 2002, we include in our comparison a revised estimate of magnitudes with the same procedure applied for ECOS-02, but with a different intercept-intensity to magnitude relation. The change in magnitude was mostly due to the work performed by Braunmiller et al. (2005) and Bernardi et al. (2005). This change in magnitude of calibration events causes a change of the intercept-intensity to magnitude relations used in ECOS-02, which then changes the attenuation relations. The revised attenuation relations are given Appendix E-1. This leads to revised estimates of moment magnitudes for historical events.

Table 8 summarizes the results for different calibration strategies and provides up to eight magnitude estimates for each event. It is seen that in the case of large historical events, magnitudes can only be estimated with the procedures *cal_NA4CH* (with the exception of the 1295 and 1356 event), which is based on Swiss data for calibration, and *cal_NA4IT* and *cal_2004IT* that are both based on Italian data. The procedure *cal_NA4CH* cannot be used for the 1356 event because the IDPs in the epicentral area have mostly intensity 8 and 9.

The hybrid calibration *cal_ECOS09_2004IT* gives lower magnitudes than the non-hybrid strategies, except for the 1356 event. This is caused by the coefficients for the intensity class 7 that are not very reliable and lead to smaller magnitudes. The magnitudes are given in parenthesis and are too low, and should not be used to characterize the event.

The procedure using the maximum intensities Imax has an effect on the 1295, the 1356 and the 1584 events only. For the other events, magnitudes do not change when using the most probable intensities (Iw) or the maximum intensities (Imax).

Since all of the calibration procedures are reasonable, the variability in the magnitude provides a base to estimate epistemic uncertainty related to the calibration method.

Event number	Year	Month	Day	Hour	Event Name	Mw (bestmag)[(1)]	ECOS-02[(2)]	Revised ECOS-02[(3)]	BxMw[(4)]	BxMw[(5)]	BxMw[(6)]	BxMw[(7)]	BxMw[(8)]	BxMw[(9)]	BxMw[(10)]
295	1295	09	03	00	Churwalden	-	6.5	6.2			6.0	6.1	6.5	(5.7)	(5.85*)
545	1356	10	18	21	Basel	-	6.9	6.7			6.3	6.4	6.7	6.3	6.9
572	1584	3	11	11	Aigle	-	6.4	6.1		5.6	5.6	5.8	6.1	(5.3)	(5.9)
31	1601	9	18	1	Unterwalden	-	6.2	5.9		6.1	6.2	6.1	5.9 #	(5.7)	(5.7 **#)**
82	1685	3	8	19	Mittelwallis	-	6.1	5.9	(5.3*)	5.8*	5.4*	5.6*			
22	1755	12	9	13	Brig-Naters	-	6.1	5.9		5.8	6.1	6.1	6.1		
49	1770	3	20	15	Château-d'Oex	-	5.7	5.5	4.9	5.4	5.3	5.2			
1117	1855	7	25	11	Törbel	-	6.4	6.1		5.9	6.1	6.1	6.1	(5.4)	(5.6)
239	1905	12	25	17	Domat-Ems	4.7 (-)	4.8	4.7	4.5	5.1	5.1	4.9			
241	1905	12	26	0	Tamins	-	5.1	5.0	4.6	5.2	5.1	4.9			
1110	1913	7	20	12	Ebingen	-	5.2	5.1	4.7	5.3	5.3	5.2			
1036	1929	3	1	10	Bioley-Magnoux	5.0	5.3	5.0	4.3	4.9	5.1	5.0			
20009	1946	1	25	17	Ayent	5.8	6.1	5.8	(5.3)	5.8	6.0	5.9	5.9	(5.4)	(5.5)
20007	1946	5	30	3	Ayent	5.5	6.0	5.5	5.2	5.6	5.6	5.6			
1086	1978	9	3	5	Ebingen/Swabian Jura	5.5	5.15	5.5	5.1	5.6	5.6	5.6			
1098	1991	11	20	1	Vaz/GR	4.7	4.6	4.7	4.7	5.3	5.1	5.1			
51355	2004	12	5	1	Freiburg	4.5 (-)	4.9	4.5	4.8*	5.4*	4.9*	4.9*			

Table 8. Results obtained for the magnitude for historical events using different calibration procedure ((-): Event does not belong to the Swiss calibration dataset used for cal_ECOS09; ****:*** *magnitude estimated from the epicentral intensity; #: Epicenter location too far from historically assumed epicenter; ( ) numbers in parenthesis are too low due the influence of calibrated coefficients of intensity 7 in the cal_ ECOS09 procedure):*

1. *Mw(Bestmag): Mw derived from instrumental recordings.*
2. *Mw presently in the ECOS-02 catalogue.*
3. *Revised Mw due to changes in magnitudes of the calibration events used for ECOS-02.*
4. *Magnitude estimated from the cal_ECOS09 procedure (only for the events with epicentral intensity smaller than 9), using the usable highest three intensity classes.*
5. *Magnitude estimated from the cal_NA4CH procedure (only for the events with epicentral intensity smaller than 9), using the usable highest three intensity classes.*
6. *Magnitude estimated from the cal_NA4IT procedure, using the usable highest three intensity classes.*
7. *Magnitude estimated from the cal_2004IT procedure using the usable highest three intensity classes.*
8. *Magnitude estimated from the cal_2004IT procedure using the usable highest three intensity classes and Imax for each event.*
9. *Magnitude estimated from the cal_ECOS09_NA4IT procedure using the usable highest three intensity classes.*
10. *Magnitude estimated from the cal_ECOS09_NA4IT procedure using the usable highest three intensity classes and Imax for each event.*

6. Conclusions

We applied the Boxer method to calibrate historical earthquakes that occurred in Switzerland. This exercise serves to cross-check the calibration performed for the Earthquake Catalogue of Switzerland 2009 (ECOS-09) using the methodology introduced by Bakun and Wentworth (1997). The macroseismic earthquake parameters are epicenter location and magnitude.
From the work we can draw the following conclusions:

- Low intensity data (intensities less than or equal to 2) should be removed from the calibration dataset and the events for which the estimation of earthquake parameters is performed.
- A good performance of the calibration procedure is achieved by restricting the calibration dataset to a limited magnitude range. In this work two different calibration datasets have been computed: for events with magnitudes lower than 4.2, and for events with magnitude larger than 4.0. In the application to historical events, the coefficients from the calibration dataset with events with magnitudes larger than 4 are generally applied.
- In the validation of the calibration procedure, it has been shown that the estimation of macroseismic location is robust whatever calibration strategy is used.
- In the case of the macroseismic magnitude assessment, the performance is better when using only the coefficients corresponding to the usable three highest intensity levels of the macroseismic field of the event.

Within the magnitude range of the Swiss dataset of historical events, there is a need to assess parameters for earthquakes larger than the events in the Swiss calibration dataset. The Swiss calibration dataset does not provide reliable coefficients for the Boxer code above a moment magnitude of about 5.6-6.0. Therefore we have to include calibration coefficients that cover earthquakes with magnitudes above this limit. This has been achieved using results from Italian studies. The different calibration coefficients have been tested, including a hybrid strategy that combines the Swiss calibration with Italian calibration coefficients. The results are variable in the sense that there is not one calibration strategy that performs the best for all events and magnitude ranges. Since all of the calibration procedures are reasonable, the variability in the magnitude provides a base to estimate epistemic uncertainty related to the calibration method.

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Appendix E-1: Revised attenuation model ECOS-02

Epicentral location and magnitude of historical events was last assessed during the revision of the Earthquake Catalog of Switzerland (ECOS02) (Fäh et al., 2003; Swiss Seismological Service, 2002). ECOS provides a uniform estimate of the moment magnitudes (Mw) for all historical and instrumental events. The historical events were assessed following the proposal of Bakun and Wentworth (1997). This uniform earthquake size estimate in terms of magnitude required a magnitude/intensity calibration based on a calibration dataset of earthquakes in the 20th century for Switzerland and adjacent areas (Fäh et al., 2003). A distance weighting function was used, with observations at near distances preferentially weighted to improve the resolution of the epicentral region. The weight is zero for distances larger than 200km. Fäh et al. (2003) proposed attenuation relations for sources in the Alpine and Foreland regions, both relations were developed for shallow events (~ 0-7km depth) and deep events (~ 8-20 km depth). For any event with a magnitude larger than 5.5, the relation for deep events was selected for calibration. All the attenuation relations have a bilinear form with a hinge at about 55km epicentral distance. The relations can be summarized as follows: For sites in the range up to 55 km epicentral distance, the following attenuation model is used:

Shallow events: $I_{exp} = 1.27 * M_w – 0.043 * D + 0.096$
Deep events: $I_{exp} = 1.44 * M_w – 0.030 * D – 1.73$

I_{exp} is the EMS98 Intensity value at the site; D is the distance (km) from the source location to the site. For sites in the 55-200 km distance range the attenuation relations are as follows:

Shallow foreland events: $I_{exp} = 1.27 * M_w – 0.0115 * D – 1.65$
Shallow alpine events: $I_{exp} = 1.27 * M_w – 0.0064 * D – 1.93$
Deep foreland events: $I_{exp} = 1.44 * M_w – 0.0115 * D – 2.76$
Deep alpine events: $I_{exp} = 1.44 * M_w – 0.0064 * D – 3.04$

The constants were derived from the calibration set of events in the magnitude range up to Mw 6.1. The procedure for ECOS02 separates the location and magnitude determination by defining the intercept intensity (Intensity at zero epicentral distance). The intercept intensity is related to the moment magnitude through a linear relation.

Shallow : $M_W = [I_{int} – 0.096] / 1.27$ (3)
Deep : $M_W = [I_{int} + 1.73] / 1.44$

Because magnitudes of calibration events changed after 2002 mostly due to the work performed by Braunmiller et al. (2005) and Bernardi et al. (2005), the intercept-intensity to magnitude relations had to be revised for this work using the new moment magnitudes published in Bernardi et al. (2005). The new magnitude to intensity-intercept relations are as follows, using the same calibration events as in ECOS02 however with the magnitudes published in Bernardi et al. (2005):

Shallow event: I_{int}= -0.9079+1.5248 Mw
Deep Event: I_{int}= -2.8941+1.7196 Mw

This results in a change of the magnitude for the historical events published in ECOS02:

Shallow events: $Mw_{new}= (1.27*Mw_{ECOS02}+0.096+0.9079)/1.5248$
Deep events: $Mw_{new}= (1.44*Mw_{ECOS02}-1.730+2.8941)/1.7$

Figure A.1 illustrates the influence of the change in the magnitudes of the calibration events for shallow events (upper part). The old and new linear relation between magnitude and intercept-intensity are shown in the lower part. Figure A.2 illustrates the same for deep events. The final relations and coefficients for the attenuation relation are listed in Table A.1.

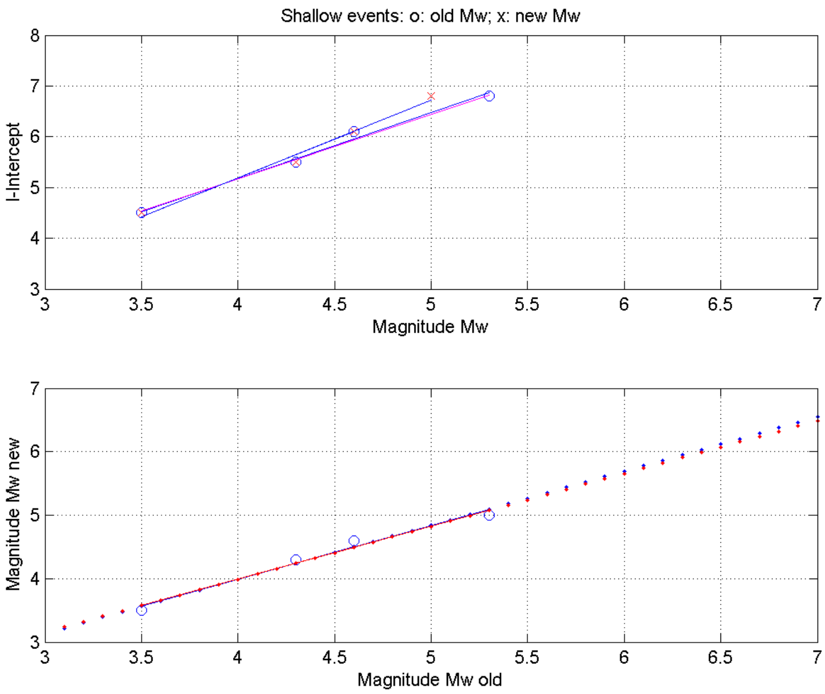

Figure A.1. Upper part: Changes in the magnitudes of the calibration events for shallow events: circles correspond to the magnitudes used for ECOS02 whereas crosses correspond to the new magnitudes. The old and new linear relation between magnitude and intercept-intensity are shown. Lower part: Change of the magnitude for the historical events in ECOS02 due to the changes of the magnitudes of the calibration events,

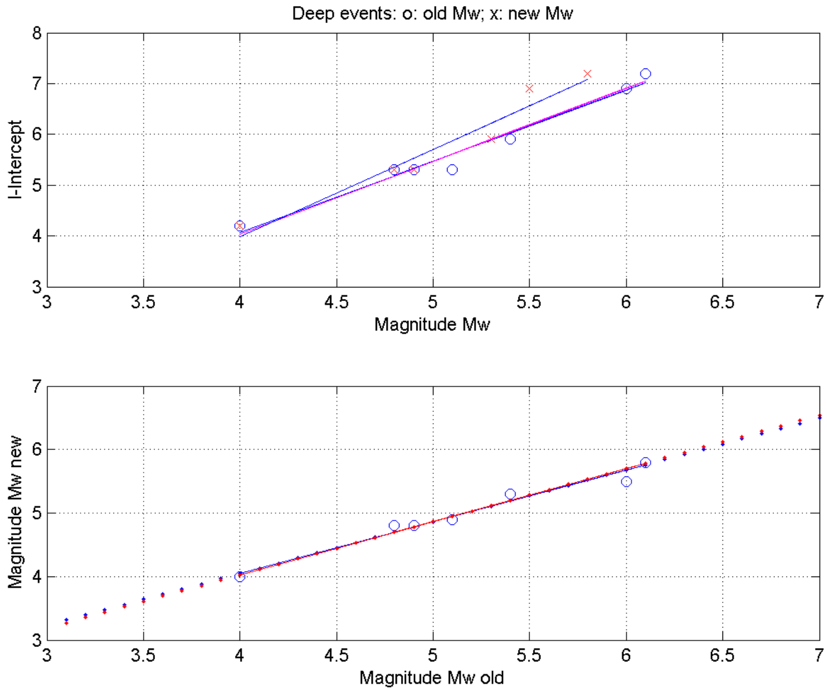

Figure A.2. The same as in Figure A.1 for deep events.

ECOS02 (Revised)	**Relation [I = I (Mw, D)]**	**st. dev.**
D<55 km, Shallow	I = - 0.9079 + 1.5248*Mw - 0.0430*D	0,62
D<55 km, Deep	I = - 2.8941 + 1.7196*Mw - 0.0300*D	0.57
D>55 km, Shallow-Foreland	I = - 2.6539 + 1.5248*Mw - 0.0115*D	-
D>55 km, Shallow-Alpine	I = - 2.9339 + 1.5248*Mw - 0.0064*D	0.59
D>55 km, Deep-Foreland	I = - 3.9241 + 1.7196*Mw - 0.0115*D	0.71
D>55 km, Deep-Alpine	I = - 4.2041 + 1.7196*Mw - 0.0064*D	0.58

Table A.1. Attenuation relations and coefficients for the revised ECOS-02 attenuation model.