STUDY OF THE RELATION "ISOEISMAL AREAS" vs "DEPTH-MAGNITUDE", BASED ON INSTRUMENTAL DATA

AUTHORS			REVIEW			APPROVAL		
NOM	DATE	VISA	NOM	DATE	VISA	NOM	DATE	VISA
A. SCHLUPP, M. DURRENBERGER C. SIRA (EOST)	14 october 2014 version finale du 30 mars 2016		T. Camelbeeck (ORB)			K. Manchuel		
			M. Mucciarelli (Università della Basillicata)			G. Senfaute		

DISSEMINATION: Authors; Steering Committee; Work Package leaders, Scientific Committee, Archiving.

Executive Summary

One of the main objectives of the WP1 of the SIGMA project is to build a homogeneous seismic catalogue for metropolitan France, especially in terms of magnitude, which covers both the historical and instrumental periods. Such a catalogue, combining long-term and short-term observations, is of primary interest when dealing with seismic hazard assessment in areas that undergo low deformation rates and low to moderate seismic activity.

The instrumental part of the catalogue has been done in the frame of the SI-Hex project [keynote lecture of M. Cara at SIGMA Scientific Committee n. 6], funded by CNRS-Universities, CEA and MEDDE. The Mw magnitude determined in the SI-Hex project for the largest events (Mw>3,4) were based on an "Mw coda method" defined in the PhD thesis of Denieul Marylin (period 2011-2014 at EOST - Strasbourg) that was supported by SIGMA/EDF. This reference catalogue gives the best available event location and homogeneous moment magnitude Mw. This catalogue is available online since March 2014 at http://www.franceseisme.fr/sismicite.html (Figure 1).

For the historical part of the catalogue, when macroseismic data are the only ones available, one of the WP1 tasks is to determine reliable seismic source parameters for the largest earthquakes, which occurred in and close to metropolitan France (Figure 1). For the depth-magnitude estimation of historical earthquakes, it is necessary to identify "proxies" in macroseismic data. Three kind of proxies based on intensity, a value of the strength of the ground shaking, could be used to estimate depth and magnitude:

Strategy A: The simplest proxy is the epicentre intensity, Io. Its value increases with magnitude and decreases with depth. The main disadvantage is that a particular Io value can be associated to various magnitudes-depths values and can be affected by strong site effects. Also, Io is most of the time not observed (there is quite never a city at the epicentre) and its estimation can be biased.

Strategy B: The second proxy is based on the use of all the IDP's (Intensity data point) and on the construction an attenuation relation for Intensity versus distance. This attenuation relation should be unique for a specific magnitude and depth if we consider a specific region and no site effect. The short distance attenuation will be mainly related to depth proxy (higher slope for shallower events) and long distance attenuation related to magnitude. Limitations of this approach come from the dependency to epicentre location and azimuthal variability of seismic motion due to attenuation (structures and/or geology) or directivity [Courboulex et al., 2013].

Strategy C: The third proxy is the isoseismals area based on all the IDP's. The advantages of this method, which was chosen by BCSF in agreement with EDF in the frame of the WP1 of Sigma, are that it is independent of the epicentre location, epicentre intensity, spatial heterogeneity of the IDP location and not sensitive to the geometry (elongation, etc.) of the isoseismals. Nevertheless, with this strategy we add one challenge that is to trace objectively the isoseismals in the way to not increase the uncertainties related to an expert draw or expert interpretation. Therefore, we decided to work first on the numerical approaches for the isoseismal draw that can be reproducible by anyone and then only on the relation with magnitude-depth using Master events.

The way followed by SIGMA WP1 to build the parametric catalogue for past events deals with the use of Intensity Data Points (IDPs) from SISFRANCE database through intensity attenuation models [SIGMA deliverable D1-108, Bonnet et al.]. This approach has the advantage that IDPs can be used directly without any pre-processing (Strategy B).

WP1 wanted to investigate another approach that also use IDPs but through the area of the isoseismals (Strategy C). Notice that this approach has not been chosen in this project to compute directly seismological parameters of historical events because of the lack of available isoseismals for all events of SISFRANCE database and the limited number of IDPs. The aim was to consider a set of selected events of the last century in France on which we will apply an automatic drawn of isoseismals, developed in this project, and to deduce magnitude-depth parameters in reference to well-constrained events.

Whatever the retained method, we need to use recent earthquakes, as reference values, to consider properly the relation between macroseismic data and depth-magnitude (Mw) values that were estimated from instrumental data..

In this work, we will use for the magnitude the Mw scale to be consistent with the new instrumental catalogue (version 2014). Their values come either from SI-Hex catalogue (for events after 1962) based on Denieul-Cara method (Seismic moment magnitude and crustal coda waves, Sigma project WP1), either from the results of Benjumea and Cara (Mw Assessment for instrumental earthquakes before 1972 in metropolitan - Sigma project WP1) or from international publications.

For the depth reference value, we will use either SI-Hex if the parameter is well constrained, either Benjumea-Cara results, or published values. Nevertheless, we have to keep in mind that the depth is the most difficult parameter to estimate, even today for most of crustal events. For that we need very close stations, which is often not the case, therefore their uncertainties can stay very large.

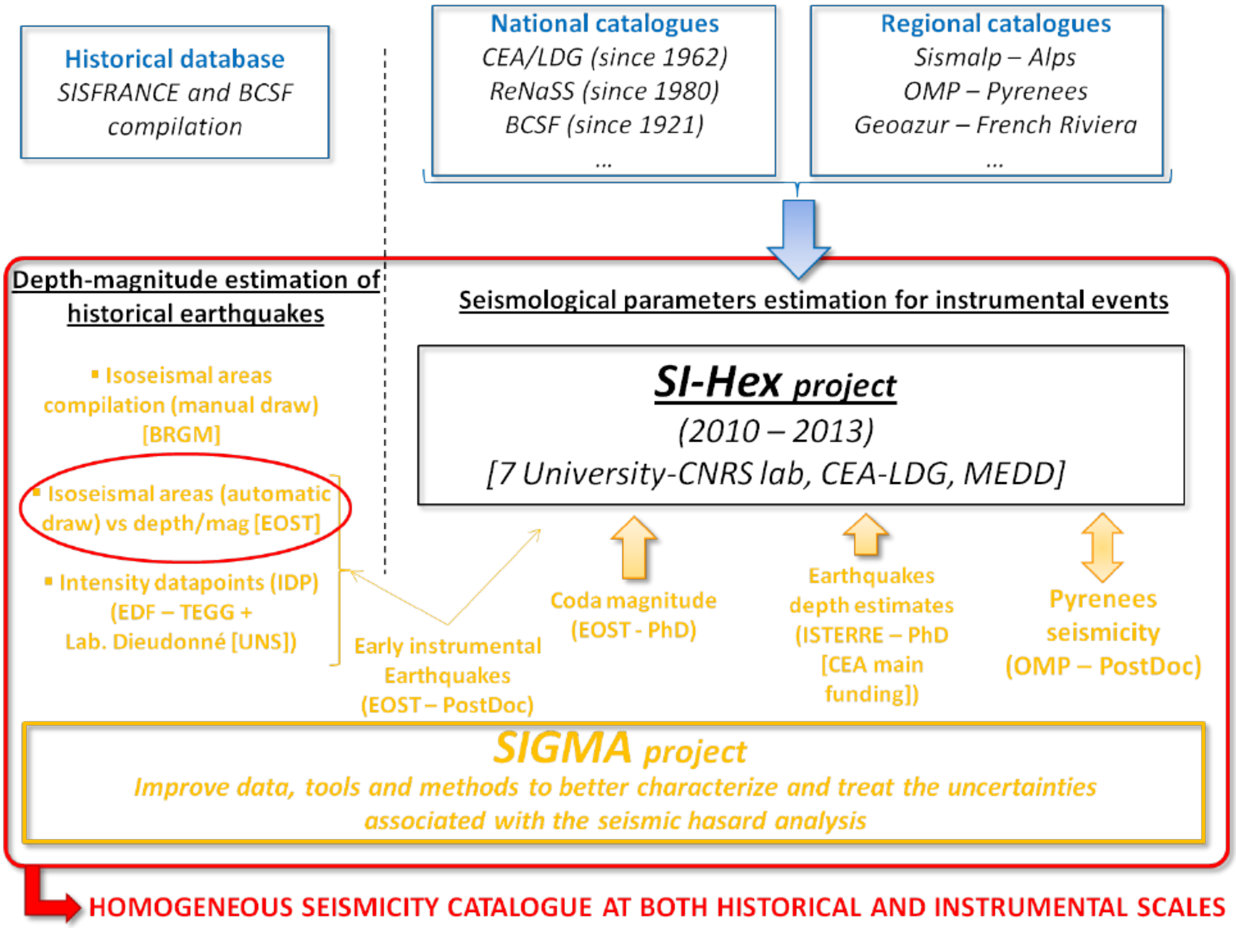


Figure 1: Actions carried out by WP1 in the framework of the catalogue task: The red box shows all the studies that are done for the final target, a homogeneous seismicity catalogue at both historical and instrumental scales. In this red box, the orange colours concerns on-going works done in the frame of the SIGMA WP1 and in black the SI-Hex project funded by CNRS-Universities, CEA and MEDDE under the coordination of BCSF and DASE/LDG. We can see that several SIGMA WP1 studies feed the SI-Hex project.
The left-hand of the dashed line is for the historical period and the right side for the instrumental one. At the top of the scheme are the various catalogue and database available before the SIGMA and SI-Hex projects. Red ellipse shows our study in this framework.

Summary

The purpose of this work was to test the possibility to use isoseismals area, deduced from observed IDP and a numerical approach to avoid "expert interpretation impact", to characterise Moment magnitude and depth parameters for earthquakes of the XXth century. The work should be based on precise instrumental parameters produced by recent work as the SI-Hex 2014 project (CNRS, Universities and MEDDE), Denieul et al. 2014 (WP1 Sigma) and Benjumea et al. 2014 (WP1 Sigma) study.

For that we tested various numerical methods and selected the interpolation using Kriging procedure. We defined adjusted parameters for local kriging after testing the method on the Rambervillers earthquakes and by simulating incomplete datasets of IDP.

The Isoseismals areas are converted in radius of circle of equivalent area. We tested the method on 22 events of XXth century with Io of VII or more.

The plot of "radius" versus intensity appears to be a very good proxy to estimate Mw and Depth by using "master events" that are precisely known. It seems to be an excellent method for depth assessment. The obtained curves are fitting well with the Bakun and Scotti 2006 attenuation relations except for Rhine and Armorica area where their relation does not fit the data.

With our method, we pointed out some events for which the instrumental values are not fitting the observations and we proposed alternative "estimations".

More events have to be analysed to produce constrained relations between our procedure and associated curves and Mw and depth parameters, particularly in the area of Armorica and Rhine.

Introduction:

Presentation of the French Central Seismological Office

The French Central Seismological Office (BCSF - Bureau Central Sismologique Français) has since its creation in 1921 the task to collect, archive and make available the seismological data related to the earthquakes on the French territory (metropolitan and oversees). Moreover, the BCSF is in charge of collecting macroseismic observations on the field and to estimates the EMS98 intensities on the French territory.

For that, for any widely felt earthquake, which corresponds to a magnitude higher than 3,7 (M_L LDG) for the metropolitan France, the BCSF collects macroseismic information by three complementary ways. Individual forms are collected by its website (www.franceseisme.fr) and collective forms are collected by an enquiry to the local authorities. If damages affect constructions, it is completed by a field survey made by the Macroseismic Intervention Group (G.I.M. – Groupe d'intervention macrosismique). The G.I.M. has today 54 members, from 15 organisations, trained especially to determine the frequency of damages for each vulnerability class following the EMS98 scale. These observations are the basis of the BCSF intensity assessment (BCSF uses EMS98 scale since 2000).

The commune or city is the minimal spatial unit used at this time for the EMS98 intensity assessment, including when data comes from citizen. The intensity value is associated at the "official" or "administrative" geographical position of the city but it characterises the strength of the shaking for the total urban area.

These intensity values are stored in a database associated with metadata and available at http://www.franceseisme.fr/donnees/BD-MFC/ (BD-MFC: Base de Données Macrosismiques Françaises Contemporaines).

For each event of magnitude M_L LDG >3.7, the BCSF has also the charge to provide a technical report, including intensity EMS98 assessment, to the French National Disaster Commission (Commission Cat-Nat) that decides which cities are classified for "natural disaster" and then damages covered by insurances.

Aim of the study: Can be Isoseismals area a proxy of magnitude/depth parameters?

The magnitude and depth are fundamental parameters of seismic catalogues. These parameters are not directly available from Intensity data. But the spatial distribution of the IDPs and the way they decrease with distance is related to theses parameters. This is illustrated in the figure 2 and 3. It shows that lower the depth is; closer are the successive isoseismals (rapid decrease of Intensity). But this relation is true only for the epicentre area, mostly at less than 20 km for a magnitude 5 after Levret et al. (1994) relation used in Figure 2 and 3. At longer distance, the level of intensity and its decrease with the epicentre distance is mainly related to the magnitude.

For event known only by IDPs, we do not know precisely the epicentre location and the epicentre intensity. Moreover, we observe that the spatial distribution of the IDPs is never regular (dependent on the distribution of cities, elongation of isoseismals and irregularity of their limits) (Figure 4). It can be related to source effect (Courboulex et al., 2013), propagation effect (spatial variation of the attenuation in the region impacted) or site effects.

The isoseismals area has the advantages to be neither dependent of the epicentre location nor on the distribution of the cities. Also, it takes into account the "non circular" shape of the isoseismals. Therefore, we decided to study if the isoseismal surfaces can be used as a proxy for the estimation of the magnitude/depth parameters for events in metropolitan France. For that, we use well-constrained events (revised magnitude Mw, depth constrained and numerous intensities available) of the last century in metropolitan France. If they can be used as proxy, we could then constrain depth for events for which there is a lack of stations at short distance or for historical events if they are enough intensity values near the epicentre. Also, we could estimate the magnitude of events before the main development of the seismic network in metropolitan France (years sixties) and, if enough observations, historical events.

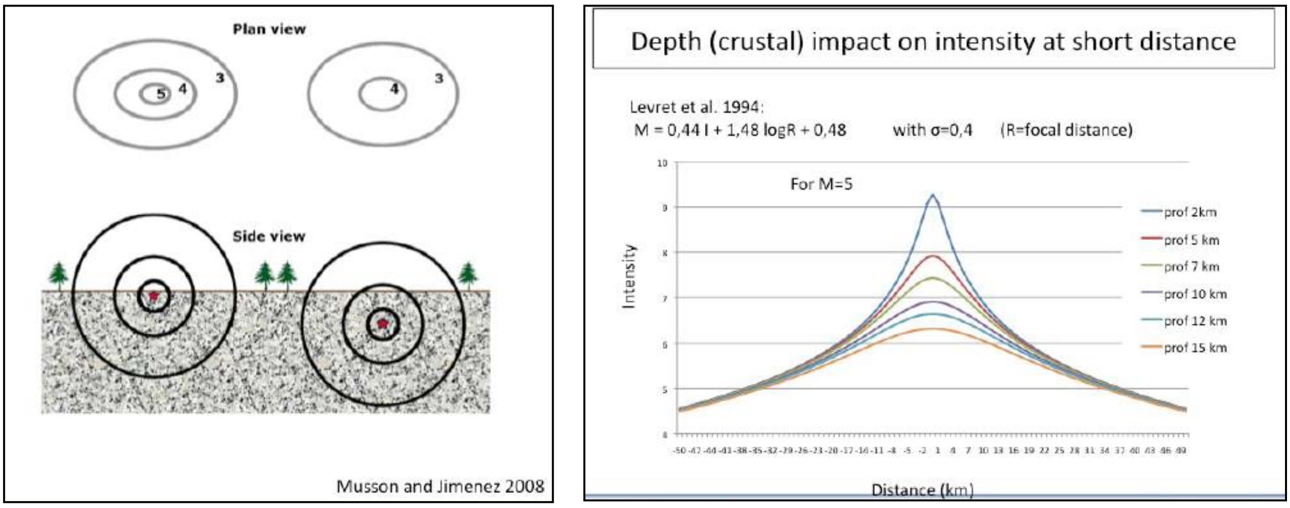


Figure 2: Impact of the depth on the isoseismals

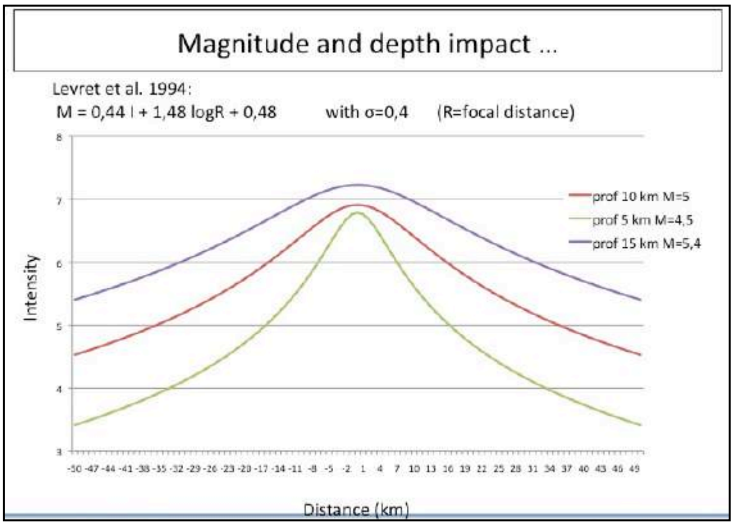


Figure 3: Impact of the magnitude and depth to the intensity

Aim of the study: How to trace isoseismals without expert interpretation?

We want to trace objectively the isoseismals in the way to avoid the uncertainties or variability related to an expert draw or expert interpretation. Therefore, we concentrated an important part of our work to define a numerical approach for the isoseismals draw. In the past, we stopped at a Semi-automatic isoseismal mapping (Cara et al. 2005 and 2007, Figure 4)

The method must be robust and applicable in most real cases, including if possible for event with a smaller number of intensities. It must be reproducible by anyone.

The method for "automatic" interpolation between observed IDPs should keep the result as close as possible from the real observed values but with a "smoothing effect". Actually, the observed data show clearly a frequent local variation of intensities. This variation seems to be mainly due to local effects (site effect) or complex propagation due to heterogeneity in the crust. One other explanation could be the low quality of available data that can induce uncertainty on the estimated intensity (over or under estimated). With our experience, this estimation uncertainty seems not to be the main origin of this variation. Nevertheless, in such case, the intensity is associated with a "low quality" code. As we are looking for a relation between source parameters (magnitude-depth) and isoseismal area, we need to smooth these variations, usually the work done by the "expert draw", but without affecting the main trend of the observations.

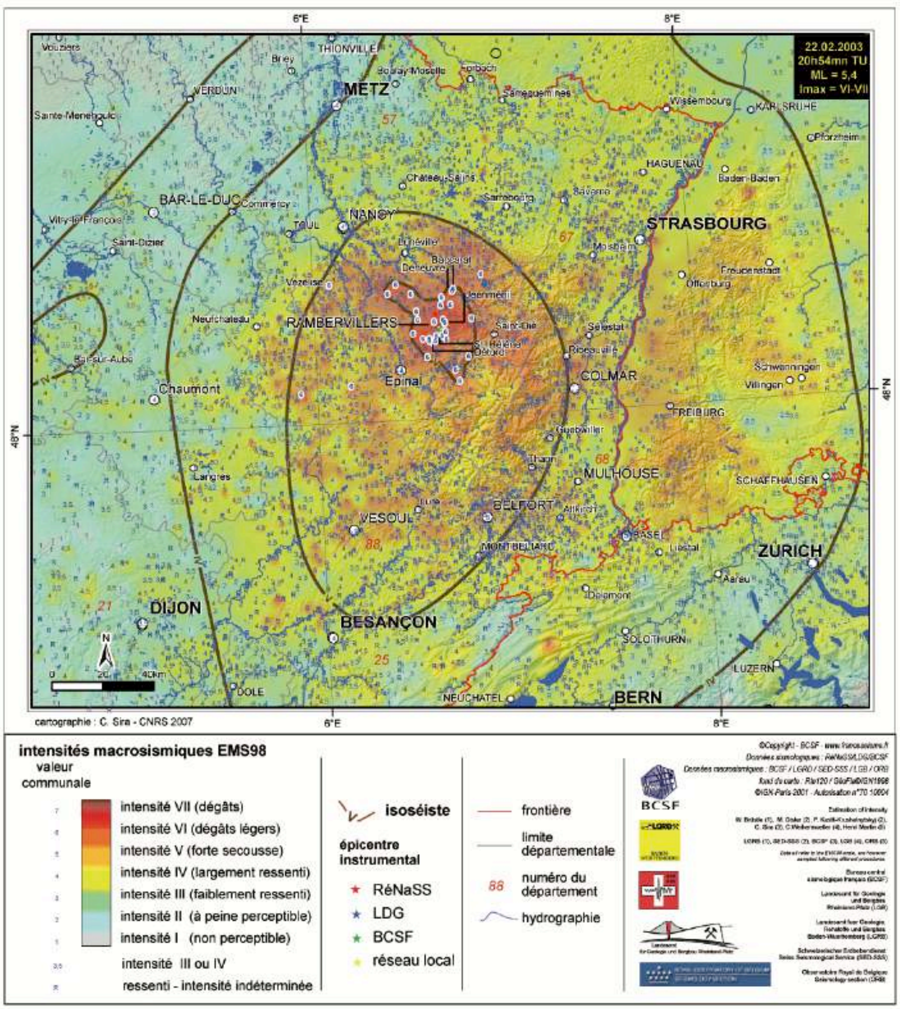


Figure 4: Semi-automatic isoseismal mapping (Cara et al. 2005, Cara et al. 2007).

The first part of the work is then to set up a standard data processing method. It should be customizable, stable, adaptable and valid for a large kind of seismic event. It should be applicable on most events included in the BCSF and Sisfrance database for the XXth century.

Methodological development for automatic isoseismal drawing and surface calculation:

Rambervillers data used for the methodological development.

In the first part of the work, we use the well-constrained Rambervillers earthquake (22 February 2003, Mw=4,8). It is the major event during the last decade in France. We have for this event in our BCSF database 5212 intensities for the French territory.

Figure 5 shows the location of the data and associated intensities values. The "circle shape" limit of the data at west is related to the limit of the survey done by the BCSF after this event. Notice that one department is empty at NW (Marne) as the prefecture did not accept to spread the form to municipalities of its department; therefore, no collective data were collected there. The other data, in Marne department and outside the circle, correspond to city for which we collected only Individual forms filled on BCSF web site. The value affected to a city in that case is the mean of the SQI (single questionnaire intensity) deduced from the individual forms.

We see that the area defined by the BCSF for the official survey through prefecture, departmental administrative office, is of first importance. The individual forms are also important, in the first minutes, hours or even days when no collective forms are available, particularly for the maximum felt distance.

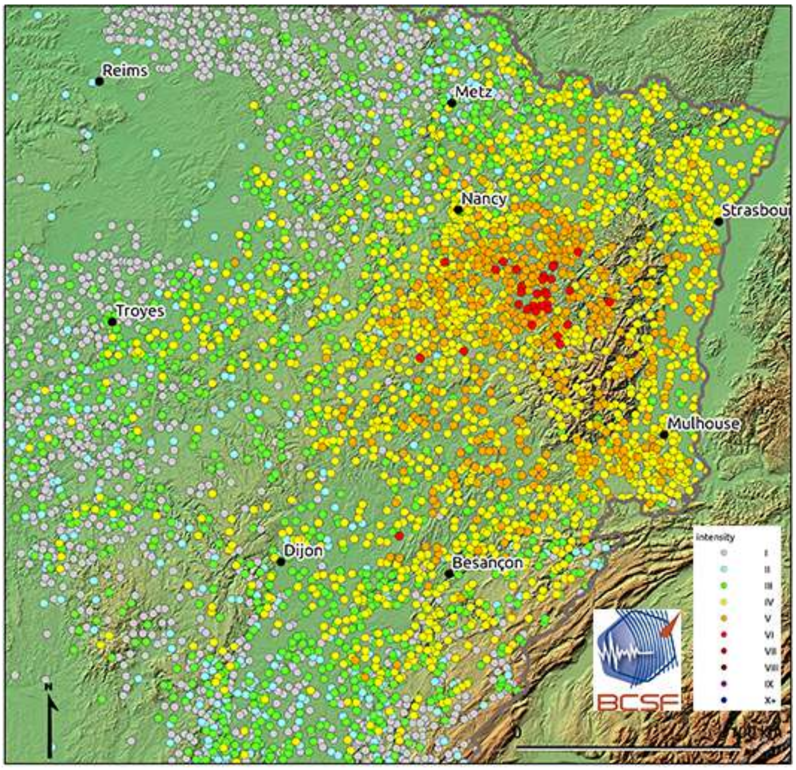


Figure 5: Intensities collected and determined by the BCSF for the Rambervillers earthquake,

22 February 2003, ML=5.4, Mw=4.9

Reduction of Rambervillers dataset for robustness control:

The dataset of macroseismic intensities, more than 5200 IDPs, is very large for the earthquake of Rambervillers, which is used for the methodological development. It corresponds to the scale of the data that we collect todays for an earthquake of intermediate magnitude (about 5) in France. However, this density of information is not representative of available data for older earthquakes and the values of intensity I (not felt) are very rarely known for the past earthquakes. So, to test our processing, we built several datasets simulating the Rambervillers earthquake as we could know him if it happened previously by decreasing the IDPs. These datasets will be used and the impact on the results evaluated. The comparison of the results will give an estimation of the robustness of the procedure.

	Intensity EMS98	I	II	III	IV	V	VI	VII
Dataset1	% of data preserved	100%	100%	100%	100%	100%	100%	100%
Dataset2	% of data preserved	0%	100%	100%	100%	100%	100%	100%
Dataset3	% of data preserved	0%	0%	25%	50%	75%	90%	100%
Dataset4	% of data preserved	0%	0%	0%	100%	100%	100%	100%

Table 1: Proportion of original IDPs in the various datasets for Rambervillers earthquake.

Dataset 1: contains all the observation stored in the BCSF database (data in France only) for the Rambervillers earthquake,

Dataset 2: contains the points of intensity higher or equal to II EMS98, simulating events as known frequently before 2000 where the “not felt” information was unknown.

Dataset 3: contains a decrease of the observed points according to the intensity value. The aim is to simulate older events where we consider that intensity I and II are unknown, that most of intensity III are not available and that half of the intensity IV are not determined. For VI to VII, we consider that most of the intensities are known as they are strongly felt and start to produce damage on weak buildings.

Dataset 4: is a step between dataset 2 and 3. It contains only intensity IV and higher considering that we loose other data (no reports). The dataset is complete until Intensity IV.

Rambervillers earthquake: Dataset type	Number of observed IDP
dataset 1: Original dataset (EMS98)	5212
dataset 2: EMS98 Intensity ≥ II dataset	3494
dataset 3: Filtered EMS98 Intensity dataset	1388
dataset 4: Filtered EMS98 Intensity dataset	2045

Table 2: Number of IDPs in the various datasets for Rambervillers earthquake.

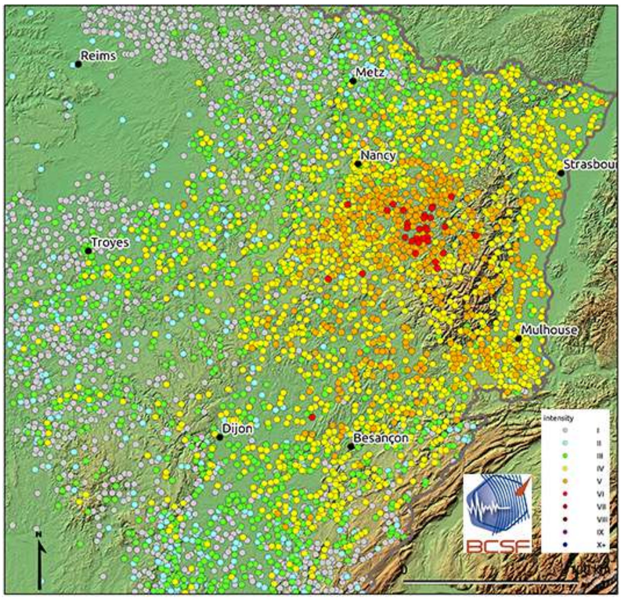
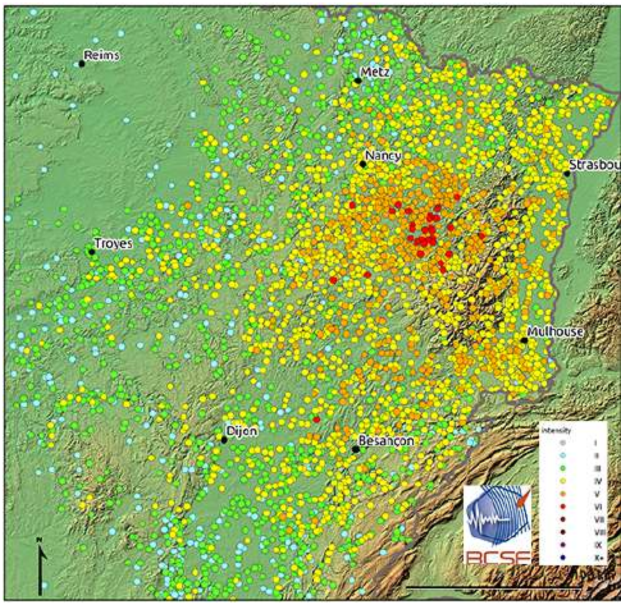
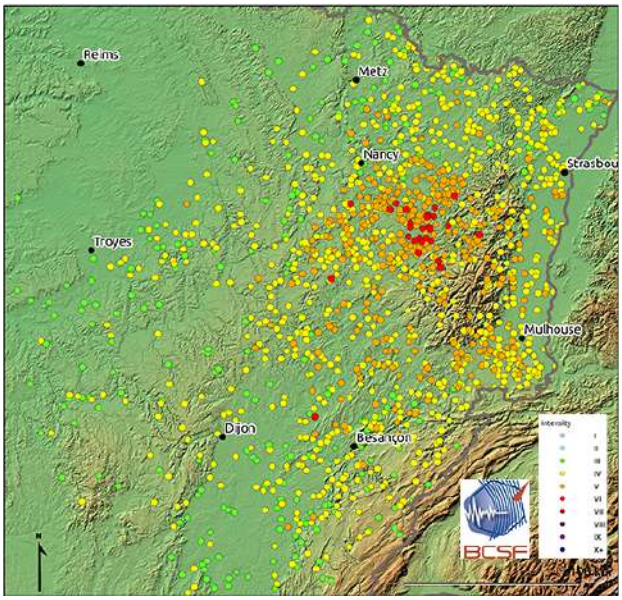
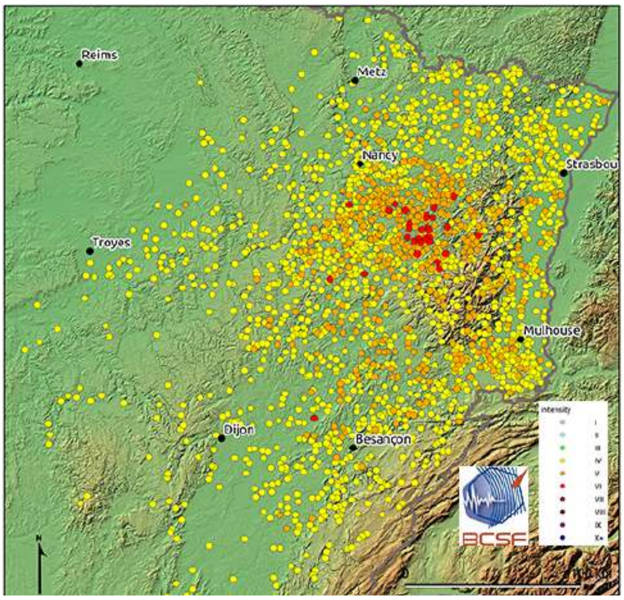
Dataset1: 5212 IDP's 	Dataset2: 3494 IDP's 
Dataset3: 1388 IDP's 	Dataset4: 2045 IDP's 

Figure 6: Map of the 4 datasets, based on Rambervillers earthquake, used in the study.

Despite this reduction of observed points, the dataset3 is still important (1388 points of observation). Notice that the largest event in France during the last century, the Lambesc earthquake (magnitude around 6, June 9, 1909), is associated to « only » about 475 observations or IDPs (Source : SisFrance web site, 2012) despite it is probably one of the best known historical event in France.

Interpolation methods investigated

Interpolation methods

Surface interpolation is any formal technique that uses values at sampled locations to predict values at non-sampled locations. The values may describe any quantitative geographic phenomenon. Common examples include elevation, rainfall, ozone concentration, temperature, and soil chemistry. In our case, it concern scatter data of intensity located at cities, therefore the region is sampled on a non-regular grid.

The Interpolation operation covers a broad range of interpolation techniques. Several methods of interpolation are available like “Natural Neighborhood”, “Interpolation”, “Bspline” and “kriging”.

We can divide the interpolation methods into two broad groups.

One is a group of deterministic interpolators. This group makes predictions from mathematical formulas that form weighted averages of nearby known values. The methods use different ways to form the weighted averages. This group includes Inverse Distance Weighted (IDW), Global and Local polynomials, and Radial Basis Functions.

The interpolation tool IDW and Spline are directly based on neighbouring observed values or specific mathematical formulae which determine the “smoothed” of the resultant surface. There are several spline types: cubic, bi cubic and thin plate for example. The spline bicubique adjusts the interior of each triangles of Delaunay, a surface the equation of which is a polynomial of rank 3. The method of the thin plate tends to minimize the effort of the surface to pass by the points of the sample.

The other group uses weighted averages as well, but also probability models to calculate predictions. This group includes “Kriging” and all of its different sub methods, including “Universal and Indicator Kriging”. Because these methods use probability calculations they are called “stochastic interpolators”.

All methods use the idea of a prediction search neighborhood, where you look at the dozen or so known values that are nearest to the prediction location and discard the rest of the data. This is done for each prediction location, so all the data are used when making an interpolated surface. Here under we present a global overview on interpolation methods that was done at the UCLA resource center (see: http://www.sppsr.ucla.edu/up206b/Interpolation_methods.htm). The various methods are well described in GIS tools. In the annexe1, annexe2 and here under we remind the main idea associated to each. We can find a good overview in the dedicated ArcGis Resource Center.

For more details see:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/Understanding_interpolation_analysis/009z0000006w000000

Distribution analysis by the decomposition of the space with the Voronoï diagram:

The decomposition of the space with the Voronoï diagram allows establishing a polygonization. Each polygon of this decomposition represents all the points of the map that are the closest to a given point (of intensity). The value of this intensity is then associated with the whole polygon. It is a simple method, of classification of data. The decomposition for every point of intensity in the space allows representing quickly the spatial distribution and the density of the macroseismic intensities.

This decomposition illustrates that the dataset for the Rambervillers earthquake is "uncompleted" in the northeast part, outside French territory, with still high intensity values at this limit (figure 7). In that case, the Voronoï diagram overvalues the intensity far from hypocentre within very wide polygons.

To calculate the isoseismal surface we should add the surface of each polygon having the same intensity value. We summarize the advantages and disadvantages of this method.

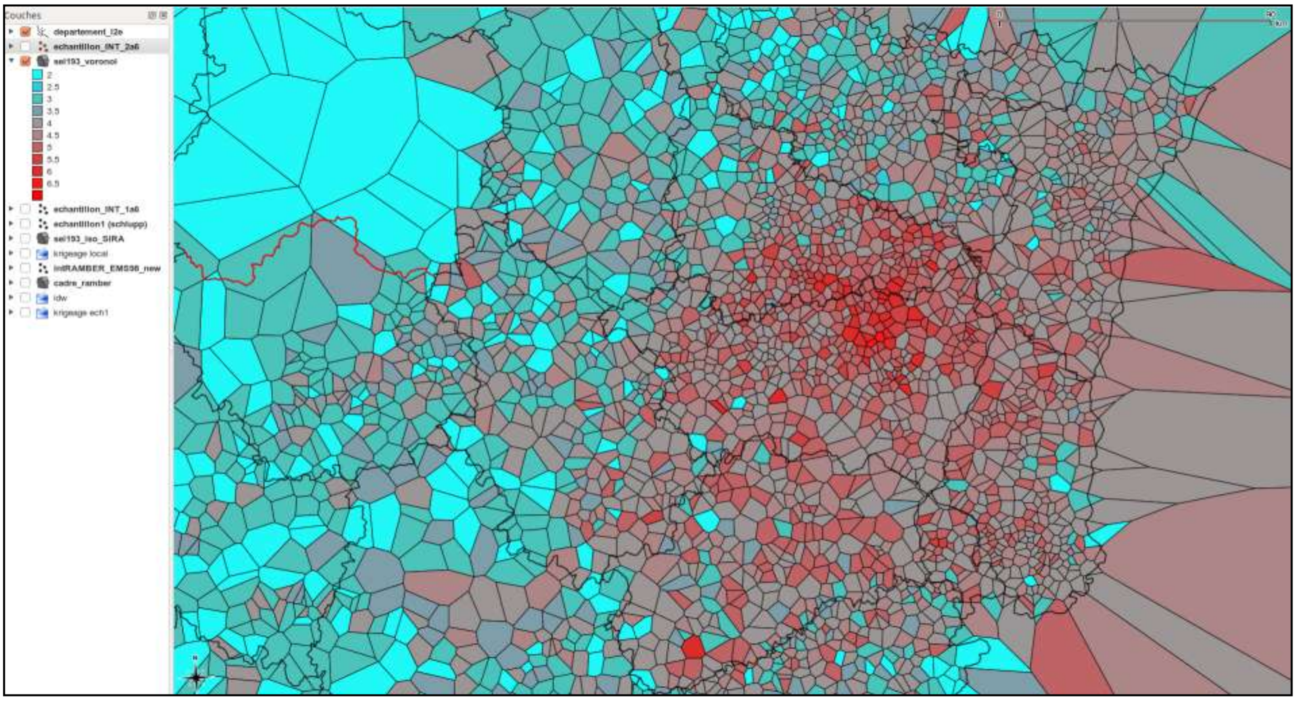


Figure 7: Voronoï polygon applied to Rambervillers earthquake

<u>The advantages of the Voronoï diagram for our purpose are.</u>

- It reproduces integer values, which is the definition of intensity
- It does not calculate new value outside the dataset values
- It considers that the nearest observation is the best value, which is a good approximation for homogeneous area (density of IDPs).
- It shows clearly local variation of observed intensity inside the global trend.

The main disadvantages of the Voronoï diagram for our purpose are

- It considers that the nearest observation is the best value, which is a bad approximation if the density of data is low, as it will widespread over large area a local variation of intensity. This variation can be due to any site or propagation effect or even to the low quality of the intensity assessment due to the lack of informations.
- It does not allow any smoothing or interpolation of the data.
- The total surface of the polygons with the same intensity is strongly related to the density of data. For example, few isolated points would contribute highly to the results, as the associated polygon will represent a large surface. Less we have data, more they will contribute to the results. We can see it in the Marne department, at the NW corner of the figure 5. Other example is a local intensity observation in France, near the country border, widespread far in Germany, where no data are available.

Refined applications of the Voronoï technique to intensity map have been done, such as the Natural-Neighbour algorithm (Sirovich et al., 2002), but it does not smooth the local variation of IDPs induced for example by local site effect. Sirovich et al. (2002) indicated: “In the n-n approach, the interpolant fits the data exactly”. Notice that the earthquake example used by Sirovich et al. (2002) does not show the real local variation of the intensity as we can observe commonly during earthquake (BCSF Database, BD-MFC) hiding this unsuitable effect.

Finally, the results are too dependent of the density of data and of the spatially isolated values as for example at the border of the area. Therefore this method is not adapted to our aim and not selected for our purpose.

Inverse distance weighted (IDW) interpolation method

We tested a second classic method: The Inverse distance weighted (IDW) interpolation method. The results of the IDW method have been used at BCSF as a guide for the “expert draw” of isoseismals.

With this method, the observed intensities are kept and the predicted values (interpolated) are dependent of the observed intensity, with a decreasing dependence with the distance (see details in the Annexe 1).

The interpolation Inverse Distance Weighted (IDW) determines the values via the weighted combination of a set of points of sampling. The weighting is a function of opposite of the distance. The weighting used in the IDW method bases mainly on the opposite of the distance raised to a mathematical power. With the parameter "Power", we can control the influence of points known on the values interpolated according to the distance, which separates them. It is a positive and real number; the value by default is 2. The definition of a higher power allows imposing a stronger influence of the closest points. So, the surface will contain more details (will be less smooth) and the interpolated values approach more and more the value of the closest point. A value of less high power gives more influence to all the surrounding points, including the most remote, what generates a smoother surface.

The resulting map and associated values will keep all observed value as they are initially. Therefore, any local variation du to local site effect or to miss-estimation of the intensity due to the lack of data will remain despite they are not related to the source or propagation effect.

The user has control over the mathematical form of the weighting function, the size of the neighbourhood (expressed as a radius or a number of points), in addition to other options.

Weighting function:
The simplest weighting function is inverse power:
w(d)= 1/dp

with p>0. The user specifies the value of p. The most common choice is p= 2. For p= 1, the interpolated function is "cone-like" in the vicinity of the data points, where it is not differentiable.

Because the formula IDW is not connected to a real physical process, there is no means to know what is the value of optimal power. Generally speaking, an important power must be used with caution. Also let us not forget that if the distances are important or if the value of power is high, prediction on remote points can be aberrant.

The choice and the control of this value will be made on the basis of the graphic results, which present surfaces by dataset and by type of interpolation according to the degree of weighting. After various tests, we concentrate on the degrees of weighting from 1 to 4.

Results with IDW method on Rambervillers earthquake.

The maps below show the area for each two weighting Degree, 2 (P2) and 3 (P3) for the datasets 1, 2 and 3 (Figure 8). Black bold lines over the results of the process are the plots of the “expert” isoseismal (Cara et al. 2005).

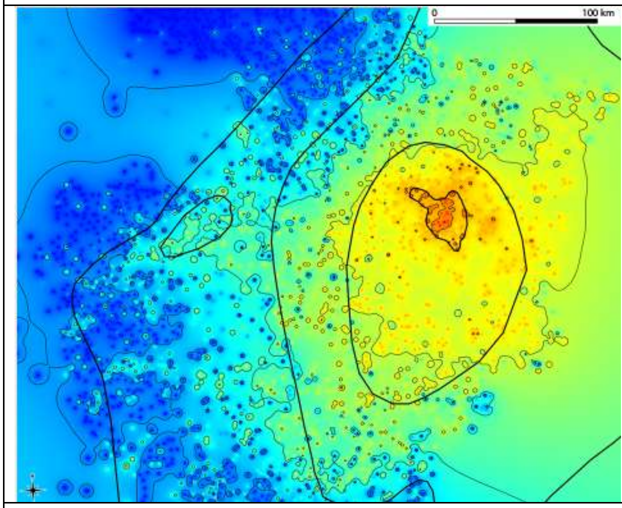
For the dataset1, we observe that the surfaces versus intensity are more or less similar to the expert isoseismal for the intensity V and VI. But they are differences for the intensity I, II, III and IV. We see clearly the impact of the IDW procedure that fits always with the observed data with local strong variations. It is also important on the border of the isoseismals IV and less.

For the dataset2, we observe that the surfaces versus intensity are again similar for the intensities V and VI. They are very strong differences for the intensity IV, and we lost the intensities I, II and III.

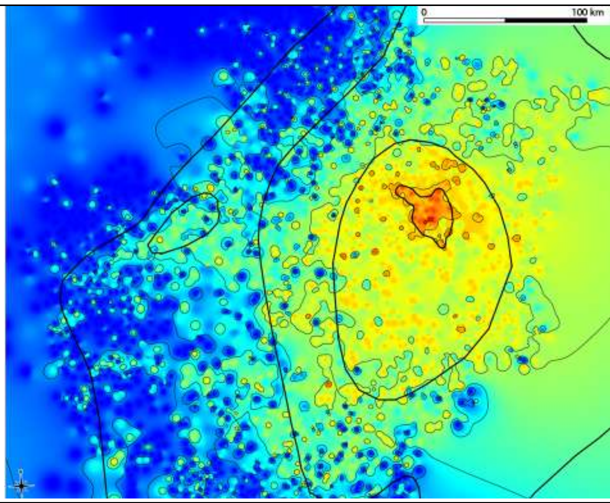
For the dataset3, we observe that the surfaces versus intensity are similar for the intensity VI, but totally different for the other intensities.

The weighting Degree 2 (P2) gives always better results that the degree 3 (P3) but its impact is much less important than the impact of the reduced dataset.

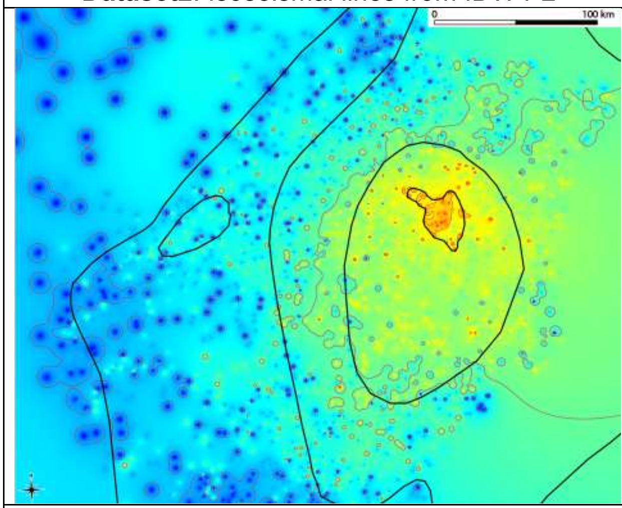
Dataset1: Isoseismal lines from IDW P2



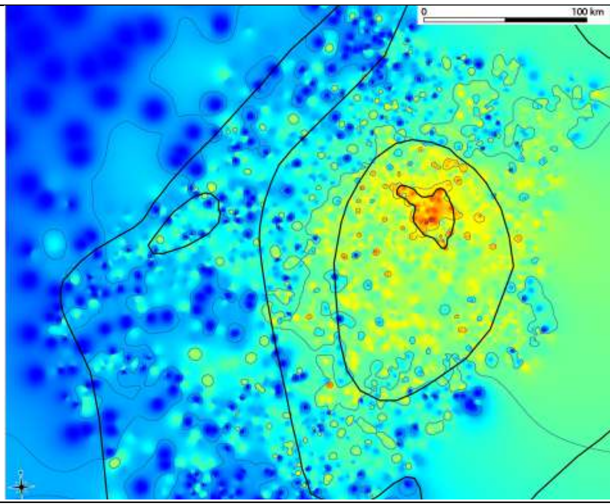
Dataset1: Isoseismal lines from IDW P3



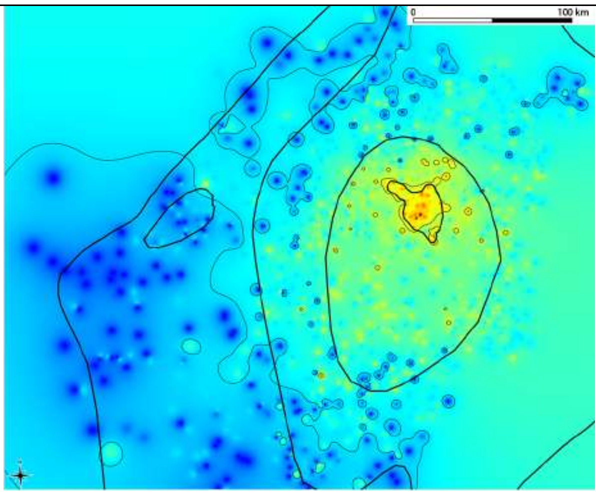
Dataset2: Isoseismal lines from IDW P2



Dataset2: Isoseismal lines from IDW P3



Dataset3: Isoseismal lines from IDW P2



Dataset3: Isoseismal lines from IDW P3

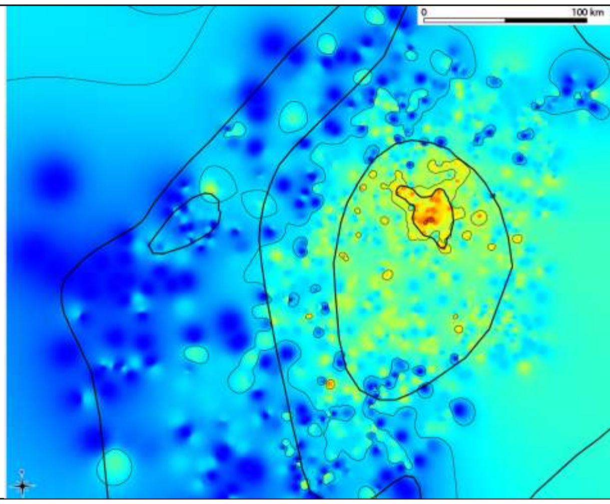


Figure 8: Comparison of IDW results for Rambervillers earthquake with the original data (Dataset1) and reduced datasets (Dataset2 and Dataset3). The "expert" isoseismals (Cara et al. 2005) are in black bold line and overlay the results of the IDW process. Intensity scale: Epicentre isoseismal is VI (orange-red) and successive ones are each with one degree less.

We plot the results of the three datasets and weighting values (figure 9 and 10) on the same graph. **To simplify the surface value and to be more near to the known attenuation laws, we convert the surface of each isoseismal to an equivalent circle (same area) and we plot the radius of the circle versus intensity. We call it "equivalent surface radius".**

We can see, that except for the intensity VI and V, the impact of the various datasets is very important with an important increase in the isoseismal area for a given intensity when the dataset is reduced.

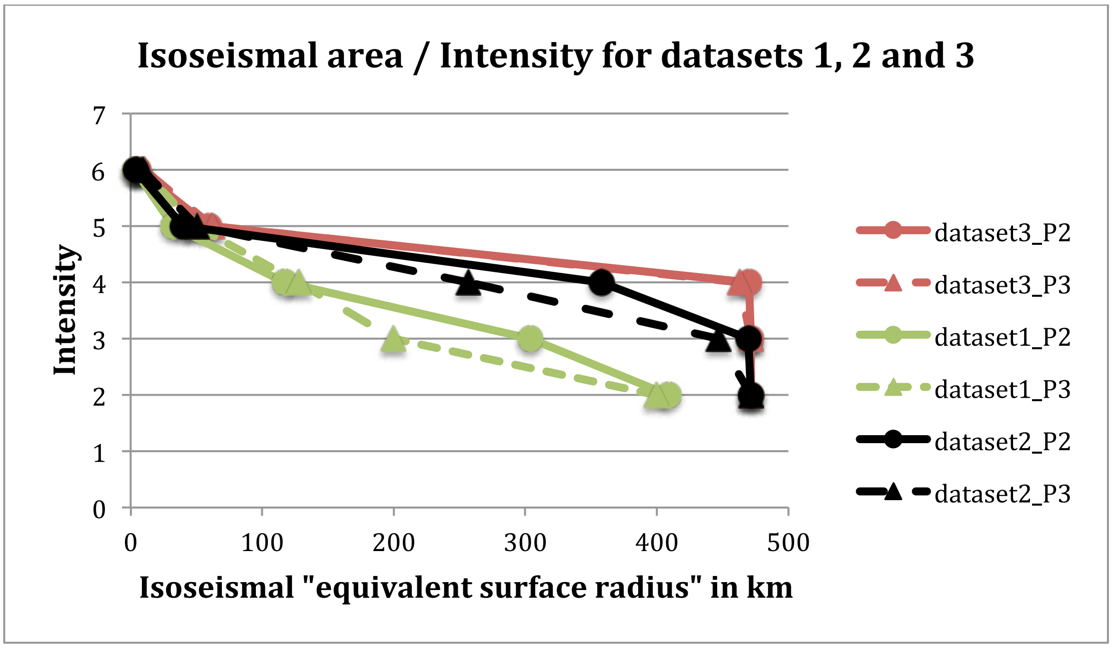


Figure 9: Comparison of the intensity area deduced from IDW for the 3 datasets and the weighting power of 2 and 3.

The advantages of the IDW interpolation for our purpose are.

- It interpolate between observed values with a weighting related to the distance of the nearest observation, which is a good approximation for homogeneous area (density of IDPs).
- It shows local variation of observed intensity inside the global trend.

The main disadvantages of the IDW interpolation for our purpose are

- It does not allow a smoothing of the data, giving a "flecked" result.
- The intensity surfaces vary a lot when using reduced dataset, effect starting very rapidly at Io minus 2 degrees (the equivalent surface radius of intensity IV vary from 130 to 465 km depending of the datasets)

Finally, the intensity surfaces vary too much when using reduced dataset for the same earthquake. Therefore the IDW method is not adapted to our aim and not selected for our purpose.

Kriging interpolation method

We summarize the kriging method (See details in the annexe 2).

This method produces an estimation of the value that is under control but calculates at each observation position a new value. It produces results near to observed values (it can give new value for observed ones) and with a global interpolation that is the "best possible" estimation using available data. For that, it uses a variogram analysis that represents the spatial correlation between pairs of observed value and shows until which distance the pairs are correlated. When the variogram decreases, the correlation between data pairs (intensities) does not follow anymore a regular tendency at this distance. This distance corresponds to the "range".

We build a function that fit at best with the variogram, at maximum until the "range " (called "limit of the model" in the figure 12).

In the ordinary kriging, the value estimation is based on the tendency and the variability of the data. We assume that there are no "a priori" tendencies in the data, and that the average value is constant. In reality, there is a tendency starting from the epicentre (decrease tendency) but we consider its exact position as unknown. This method is also appropriate to estimated value based on data for which the tendency and the directional variation are unknown.

Results with the Kriging method on Rambervillers earthquake (4 datasets).

When we apply the kriging interpolation on the 4 datasets of the Rambervillers earthquake, we see that the result is impacted by the available data. When the dataset decreases, the isoseimals areas increase (Figure 10 and 11). This is an unwanted artefact, as already observed for the IDW method. If we look back to the variogram built for each dataset (figure 12) and the deduced model, we see that the variance decreases strongly when the datasets decreases. This could be expected because the local variation in intensity is reduced as we took out the lowest values. The figure 13, showing the spatial variance of the data, illustrates it also.

This means that, when we do not have low intensity values, we do not see anymore the real local variation of the ground motion (intensity). The local variation appears smaller (smaller variance). The impact is that we overestimate the "regional" intensity and de facto the isoseismal area. This effect is probably increased for historical events for which the available data is frequently limited to high intensities.

It confirms that this variation does not come from the variogram itself but from the data and the use of **global** kriging. We will discuss this aspect later; one partial solution will be to apply a **local** kriging.

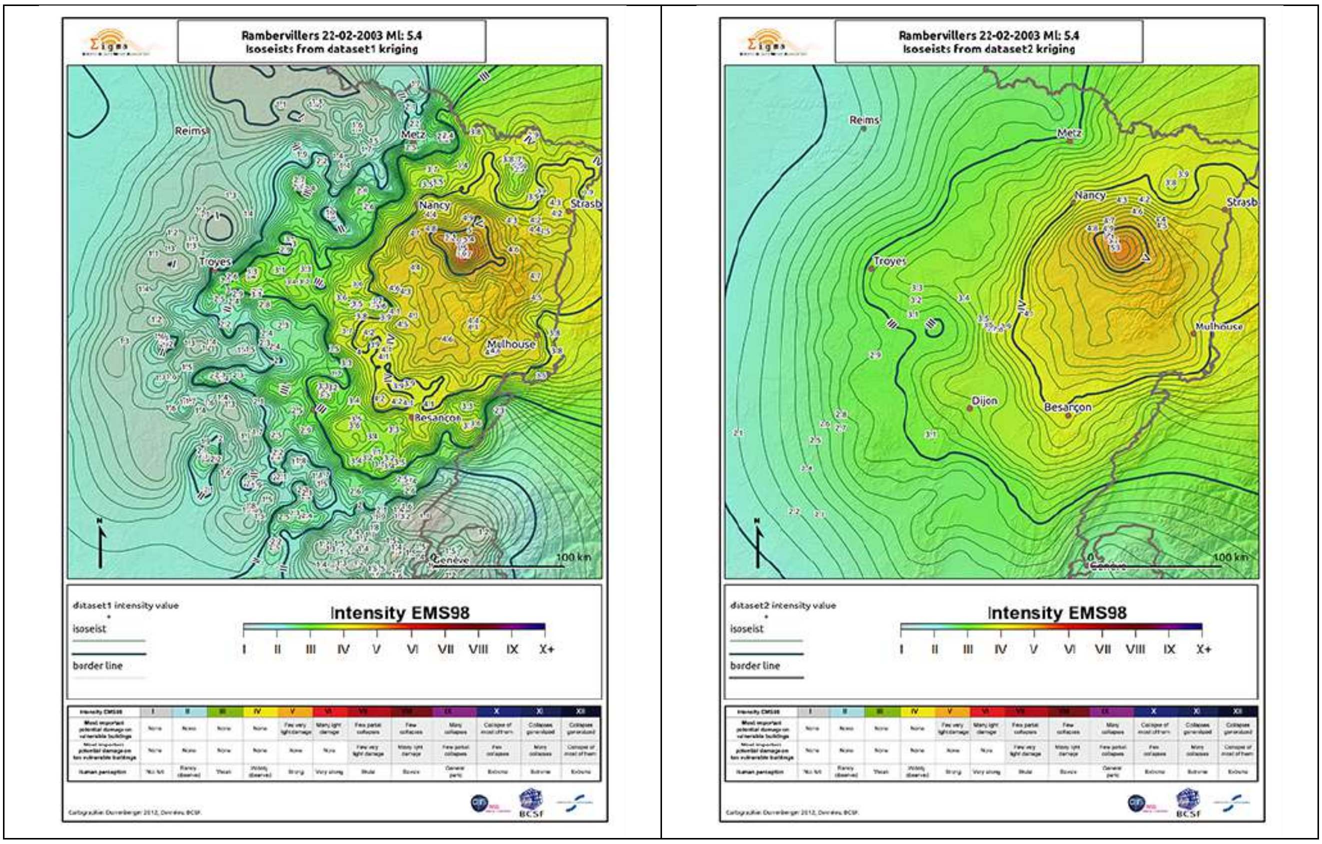


Figure 10: isoseismal following kriging method for datasets 1 and 2.

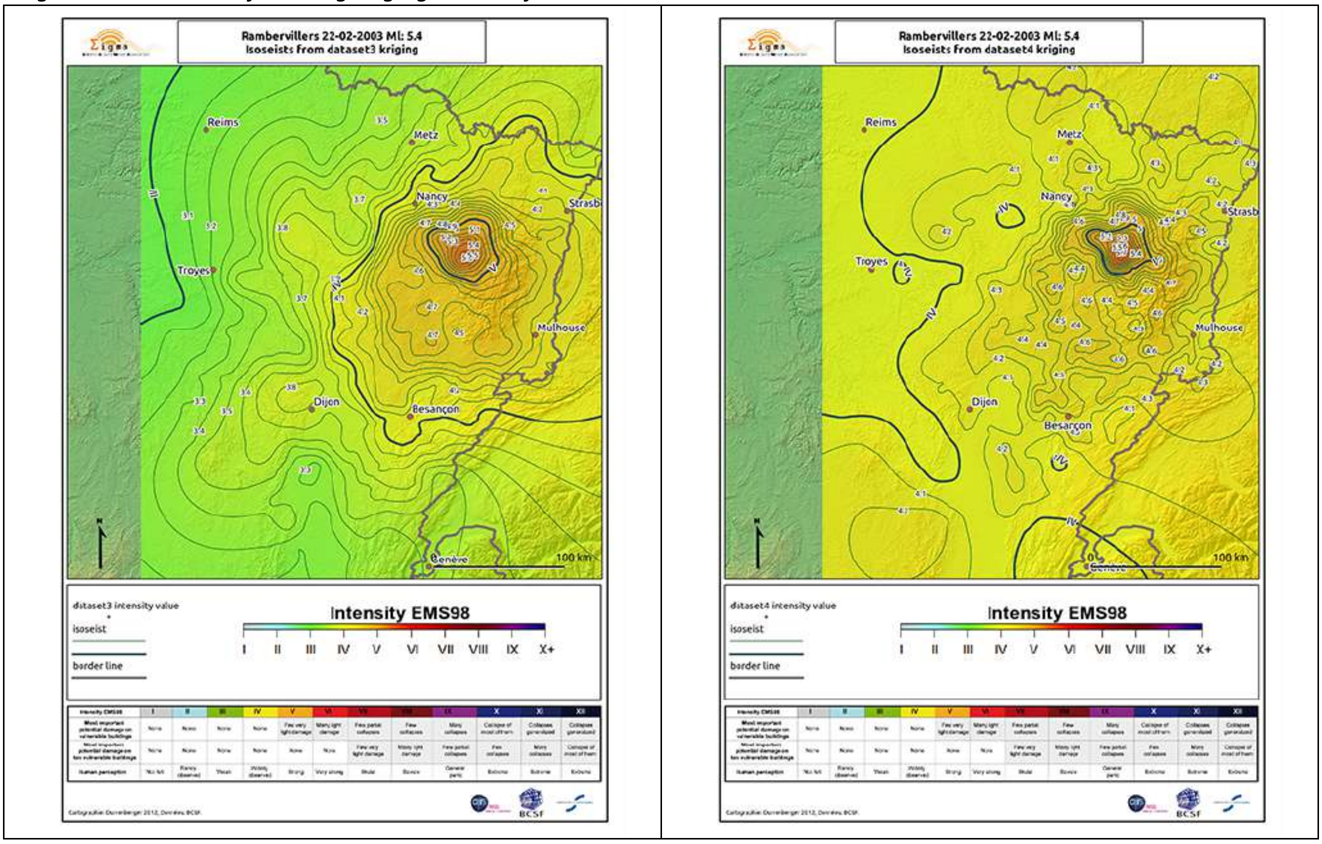


Figure 11: isoseismal following kriging method for datasets 3 and 4.

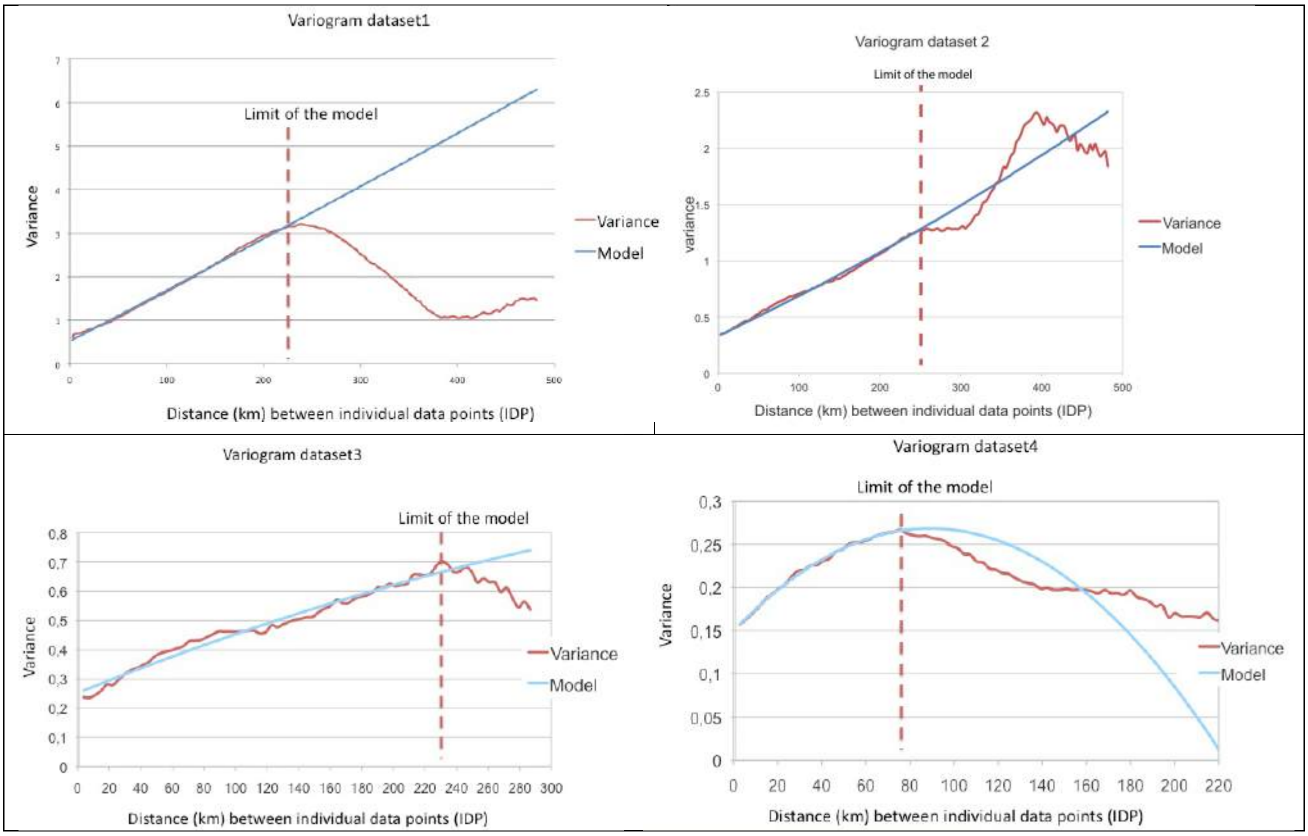


Figure 12: Rambervillers Earthquake variogram for datasets 1, 2, 3 and 4.

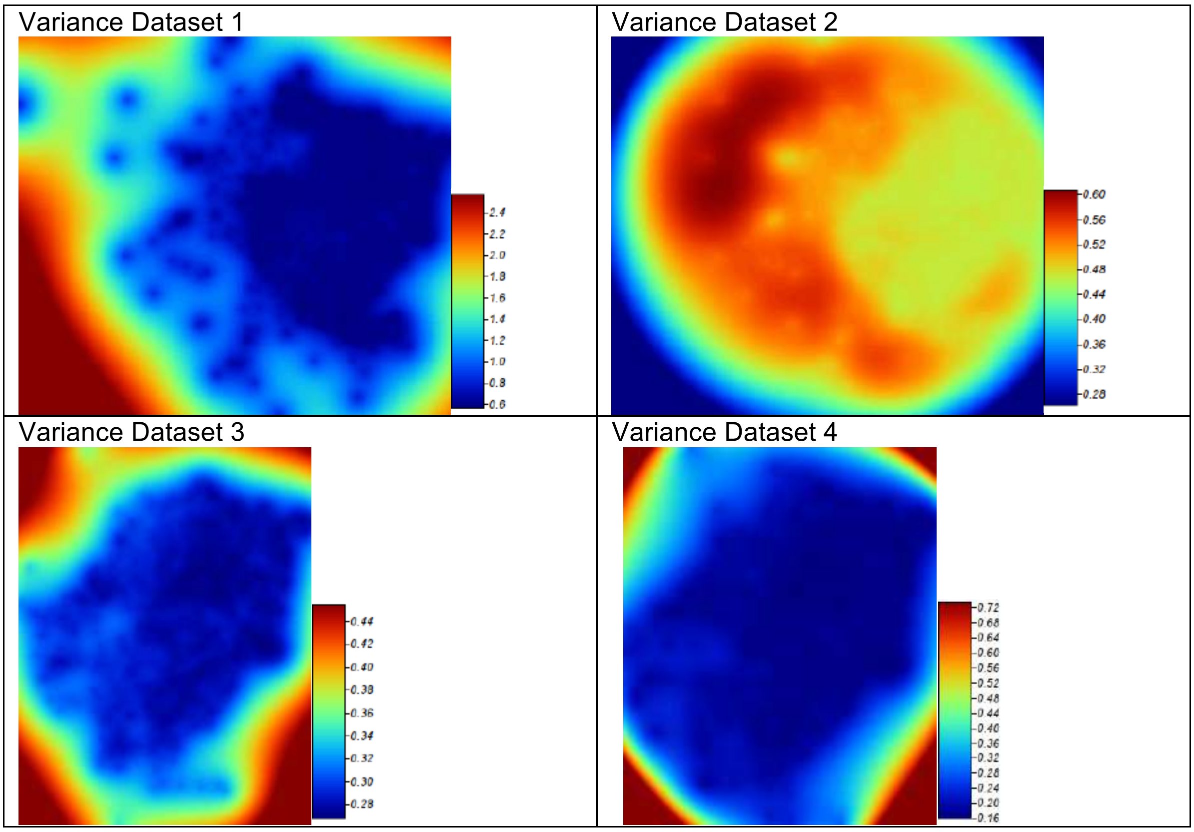


Figure 13: Variance for datasets 1, 2, 3 and 4. (Notice the colour scale is different for each dataset)

Comparison of kriging results with original IDPs

To see how close are the kriging results from the original data and then give a first statistical approach on the reliability of the method, we compare the calculated values by the kriging method with the original IDP. We observe a general trend of the difference between Intensity calculated with the kriging method and the intensity observed (figure 14). The low intensities are overestimated and the highest intensities are underestimated. This is the result of the global kriging and the associated variogram that gives the variation of intensity versus distance between pairs of IDP. When the intensities are low, we are mainly far from epicentre, and then the intensity variation with the distance is low. When the intensities are high, they are mainly related to the epicentre area were the intensity variation with the distance is important for crustal event (this variation depends also of the hypocentre depth). The variogram gives an average of these two situations. It induced overestimation of low intensities and underestimation for high intensities. As our method do not dependent of the knowledge of the epicentre and of any attenuation law, we correct it by introducing a linear correction of this tendency in the procedure (figure 14).

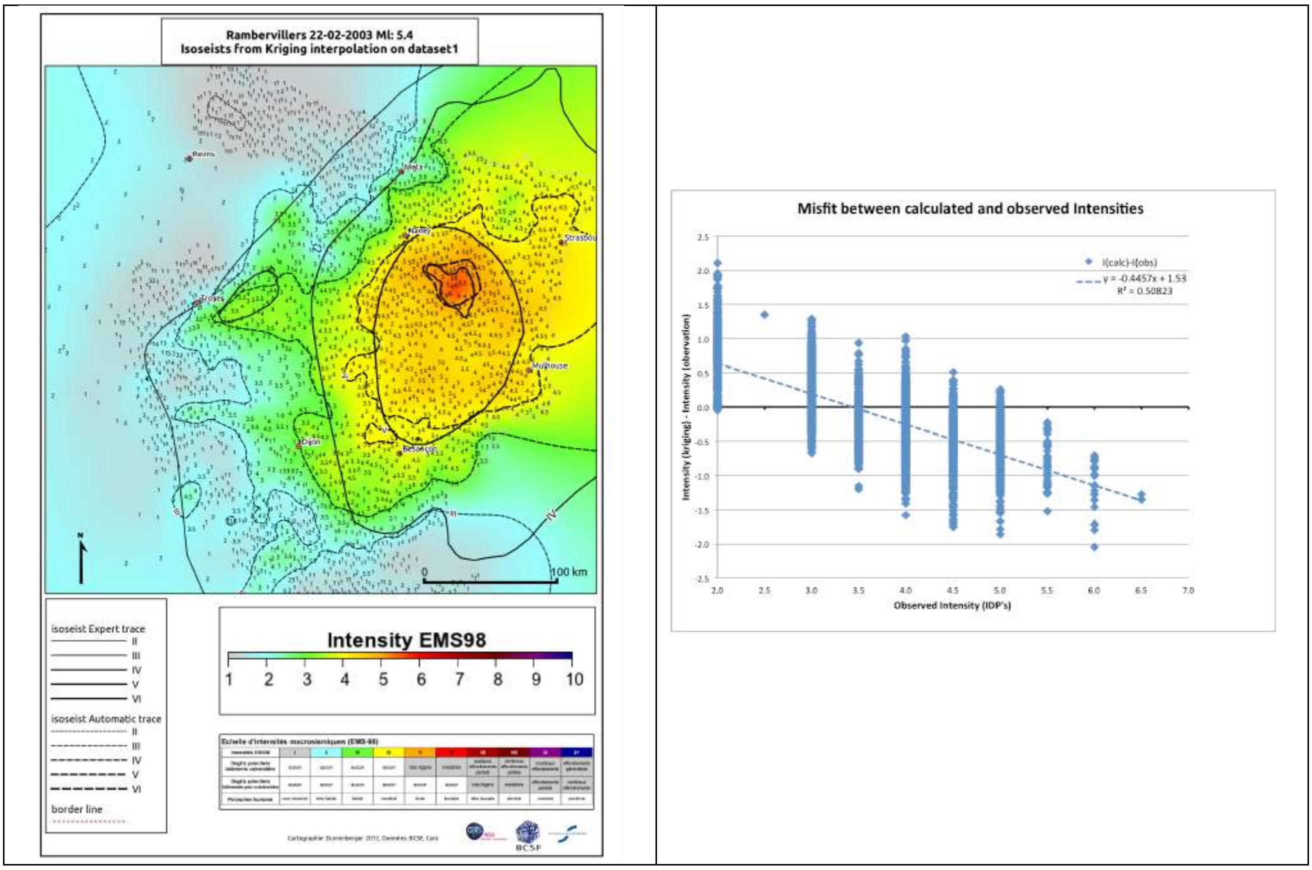


Figure 14: Illustration of the trend artefact on the results (Dataset 1).

Calculation of isoseismal surfaces and "equivalent surface radius"

The new intensity values calculated are decimal values. Each intensity point calculated is associated to a ground surface (output resolution). We add up all individual surfaces (ground resolution) between two intensity values to get the surface related to each intensity value with 0.1 steps. To simplify this surface value and to be consistent with published attenuation laws

(Intensity versus epicentre distance), **we convert the surface of each isoseismal to the radius of a circle of equivalent surface** and we plot it versus intensity. We call it "**equivalent surface radius**". The complex geometry of the isoseismal, used for the estimation of the surface, is removed by the use of "equivalent surface radius". Notice that the "equivalent surface radius" does not depend on the spatial density of the observed IDP. Also, notice that the variation of the radius (uncertainty on the estimated radius) is the square roots of the variation of the surface (uncertainty of the surface). For example an increase of 50% of the surface, which is a very important change, gives only a variation of 22% of the radius. This approach by the surface and equivalent surface radius gives a quite good stability of the procedure.

To better illustrate the decrease of the intensity with the distance, we used radius value by intensity steps of 0.1 despite only integer values characterise intensities.

At the end, we obtain a unique intensity value for a given distance simulating the events with a nearly perfect isotropic attenuation.

In the figure 15, we summarise the procedure: Variogram calculation and fit of a mathematical model, kriging calculation, Correction of the "misfit" trend if necessary and calculation of the Equivalent surface radius by 0.1 class of "pseudo-intensity".

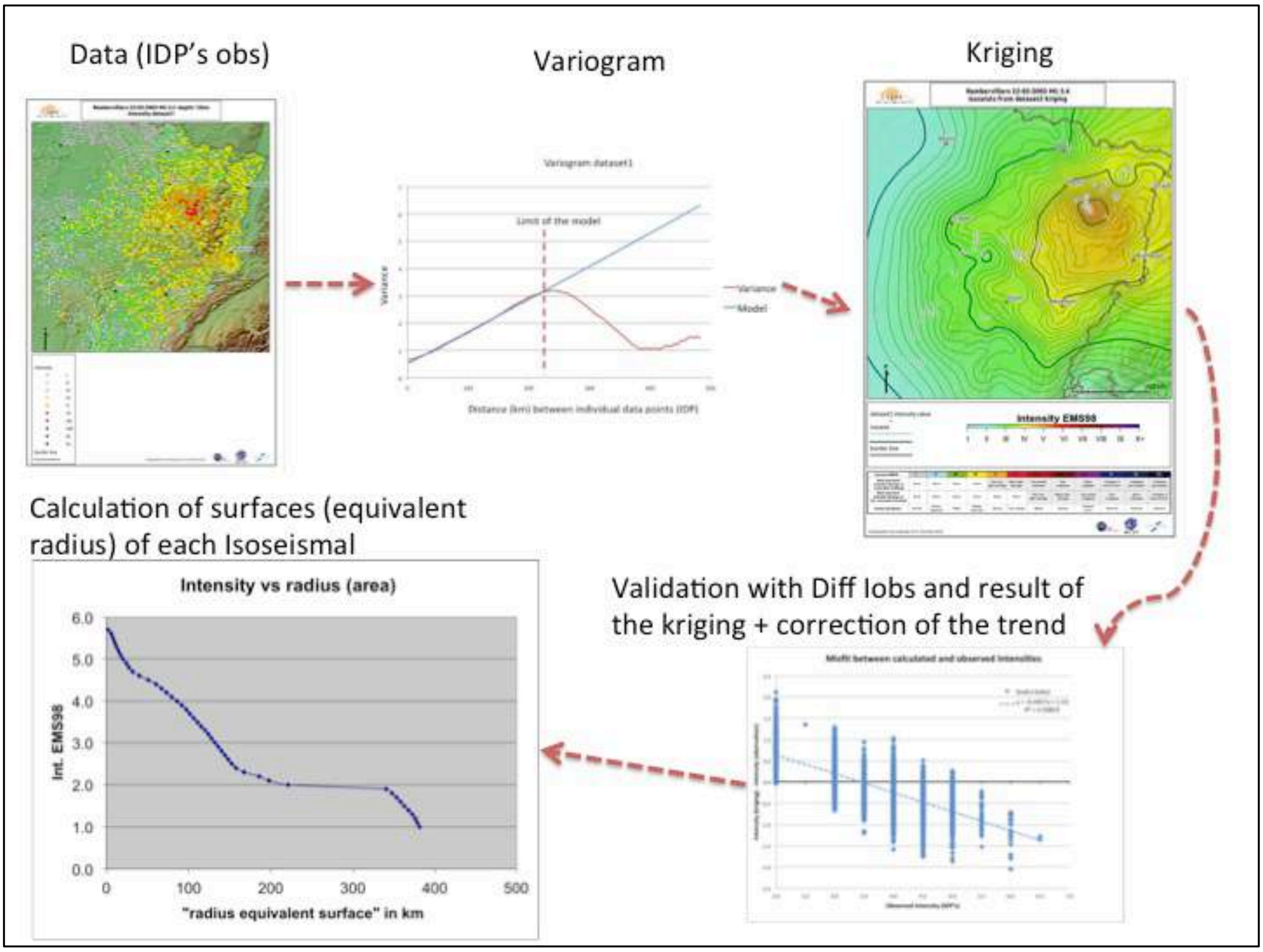


Figure 15: Schema of the kriging method, until "Equivalent surface radius" estimation,

We test the universal kriging method on the 4 datasets. The universal kriging method is applied successively; the estimation (theoretical variogram) is never inferior to the range of the original variogram.

Comparison between the results of the 4 datasets

We describe the isoseismal area for each class of intensity for each dataset based on Rambervillers earthquake IDPs. As we can see in the figure 16, the impact of the various datasets for the equivalent surface radius at less than 70 km is very small. Two main reasons are responsible of the high dispersion after. When we decrease the datasets by reducing or deleting the lowest intensities, we reduce the variability of the data and overestimate the "regional" intensity and de facto the associated surface. Moreover, as we can see on figure 11 for the dataset4, the isoseismals lower than 4,4 are interrupted by the country border and are then not constrained. The event analysis must be concentrated on region where the dataset shows the real variability of the ground shaking and without interruption of the data (shore line, country limits etc.). The exchange of data with border countries is crucial for some events.

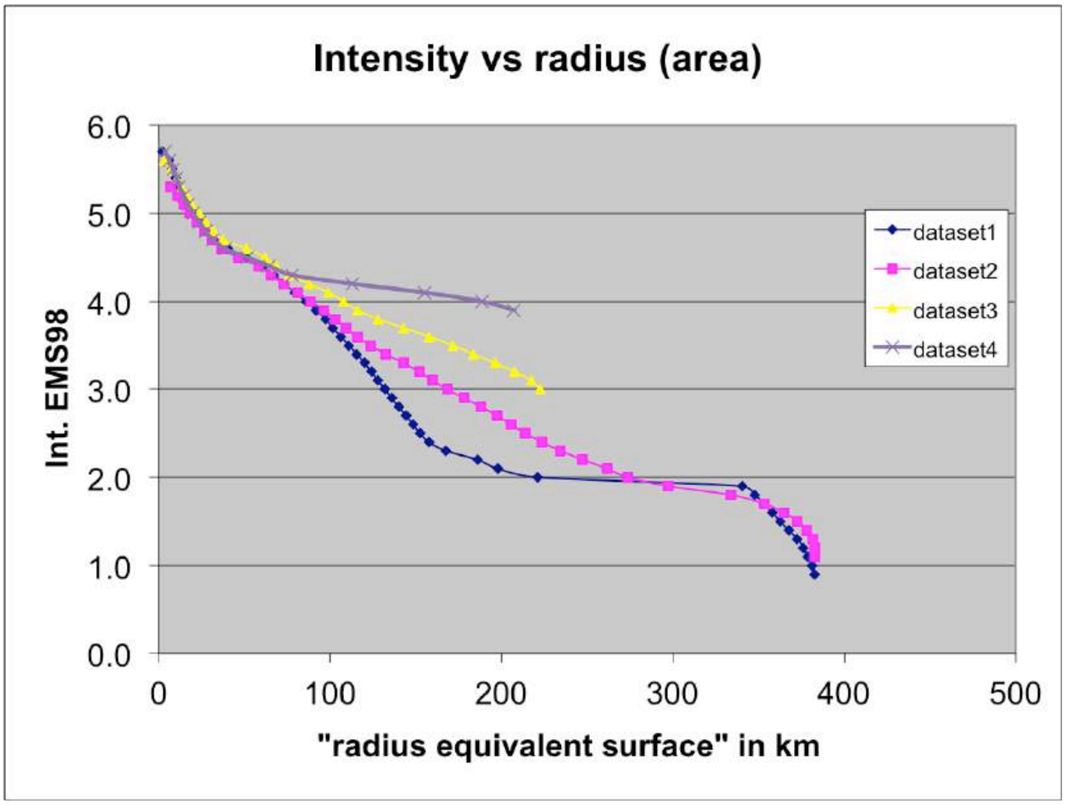


Figure 16: comparison of isoseismal area for each datasets using equivalent surface radius (cumulated "equivalent surface radius" at X axis).

Adjustment of the kriging parameters

The key of this method is the kriging model, the variogram and the associated parameters. To use the same procedure for all events and to be allowed to compare the results, we defined several optimised parameters or adjustments deduced from our tests. These parameters are applied to all studied events and datasets.

The **global kriging** interpolates IDP over an area, preliminary fixed as a geographical square, until reaching its border. To optimise the interpolation of the higher IDP values and to limit the uncertainty of the interpolation outside the dataset, we considered a **“local” kriging** with the following adjustment parameters.

Adjustment of the model on the variogram

The variogram shows the variance versus the distance between IDP pairs for the whole dataset. The variance should increase with distance, as the IDP value should vary with the distance. When the variance decrease, the IPD separated by this distance start to be uncorrelated. This distance corresponds to the “range” of the variogram. The function that fit at best this variogram is used for the kriging calculation. Nevertheless, we can use a smaller “range” to define the function or we can restrain or adjust the interpolation radius.

Adjustment of the interpolation radius

We limited the interpolation to a maximum radius around each IDP. The aim is to find a compromise between having an interpolation related to close IDP that is better for epicentre area where the variation of intensity is high, and related to more far IDPs that allows estimating intensity in area with only few observations. This distance is then much smaller than the range of the variogram and allows us to exclude interpolated value with higher error variance. It must limit the influence of far IDPs and over-interpolation at the border of the dataset.

We tested various distances between 10 and 60 km with a 10km step. The compromise has been found with a distance of 30 km that gives the best results for intensities > III.

This means that we do not calculate by kriging new IDP at a distance larger than 30km as it starts to produce unrealistic values.

Adjustment on the number of IDP used

In area with very dense IDPs, it is better to limit the number of IDP used in the interpolation to decrease the impact of the far intensities, which would include less correlated and then useless value in the procedure. Nevertheless, to smooth the interpolation and keep the advantage of the kriging method, it is also necessary to keep a minimum number of IDPs.

On other hand, in area with very few IDPs, we observed that the result is abnormal if the number of IDP used is very small. Also, we searched the minimum number of IDP necessary to obtain realistic results in the radius of 30 km.

Finally, to calculate a new IDP value we determined that the best compromise is to consider a minimum of 4 IDPs and at maximum the 10 nearest IDPs.

This means, in addition to the “Adjustment of the interpolation radius”, that we calculate new IDP only if we have at least 4 IDPs at a distance shorter than 30km. If we use shorter distance, we will frequently not be able to calculate new IDP in many areas in metropolitan France, as we will not have 4IDP (due to distance between cities or available IDP). Using longer distance will allow increasing the number of new IDP but it will strongly smooth value in epicentre area and then hide the impact of the hypocentre depth on the isoseismals area, which is the opposite of our aim.

Output resolution

The spatial resolution has been fixed to 2km to optimize the processing time for large datasets as for Rambervillers (more than 5000 IDPs). This parameter can be adapted but we advise not using higher resolution as it induces local heterogeneity especially at the border of the datasets.

Adjustment of the IDP obtained by the kriging with the observed IDP.

We remind here the misfit correction discussed previously (Figure 14). To test the quality of the results, we compared the IDP calculated with the original IDP at the same place to verify the reliability of the method. We observe for some datasets a general trend of the difference between Intensity calculated with the kriging method and the intensity observed. The low intensities are overestimated and the highest intensities are underestimated. This trend is then fitted with a linear function which is used to correct all the IDPs calculated by the Kriging. **It is important to notice that when we apply the "adjustment of the interpolation radius" and the "adjustment of the number of IDPs used" it reduces strongly this misfit.** We keep nevertheless the trend correction in the procedure.

Additional discussion on the kriging method:

Some could consider that smoothing, through the kriging approach, do not allow to take into account ground motion variability, compared to the use of attenuation base methods. Would it be reliable to use distance bins for better taking into account this ground motion variability and catching part of the uncertainties?

Behind that distance bin, there is a particular hypothesis easy but unfortunately quite never observed on modern event for which we have dense dataset: the decrease of intensity should be nearly isotropic outside local site effect and the other sources of variation are limited and associated to uncertainties. Using distance bin, we would in fact mix different value induced by the azimuthal variation of the attenuation as well as directivity of the source. If the azimuthal attenuation can vary (in that case we would be interested by an average attenuation estimation considering this variation as an uncertainty), it seems that it is not the most frequent or main origin of the variation in intensity at a given distance. The variation seems to be more related to source directivity (Courboulex et al. 2013) or regional site effect as we can observe for large sedimentary basin. The source directivity is considered, when a distance bin is used, as un uncertainty that must be smoothed, but in our approach, we want to catch totally this spatial directivity because the isoseismals area are a characteristic associate to the source itself.

Behind that question is how we can obtain an uncertainty on the results (isoseismals area)? The answer is to look for the uncertainty on the variogram at short distance (less than 30 km as it is the maximum distance we will use it), then the impacted uncertainty on the model fitting the varigram and finally the impacted uncertainty on the isoseismal area and its associated "equivalent surface radius".

Are we sure there is no effect o the stress drop in shape of intensity decrease?

If the difference is due to variation in stress drop, the impact would be mainly at short distance (for high frequencies then the discussion is possible about the depth parameter) but then this effect is also for instrumental data. Are the amplitude used corrected from possible different stress drop? This is an interesting open point that concerns not only macroseismic data. My answer is that I am not sure that there is no impact at short distance for the ground motion (instrumental and macroseismic data) but this can not be solved with macroseismic data.

Application to selected events of the XXth century

List of selected event and associated instrumental parameters

In agreement with EDF, a list of event of the XXth century has been selected to apply our kriging procedure (Figure 17). They are all events with Io ≥ VII (MSK-SisFrance) except for the Rambervillers event with Imax VI-VII (EMS98-BCSF). The selection has been made related to the number of available IDPs, their geographical distribution and the availability of constrained Mw magnitude and depth estimations (Table 3).

The IDPs, provided by EDF, come from SisFrance database (BRGM-EDF-IRSN) except for Rambervillers (2003) event characterized by BCSF IDP's (BD-MFC: Base de Données Macrosismiques Françaises Contemporaines).

In the table 3 are summarized the events characteristics as:

Event name, Mw, Mw author, Depth, Depth author, SisFrance ID, Year, Month, Day, Epic. Int. MSK, IDP numbers, Lat, Long, Catalogue used for lat-long.

The magnitude Mw comes from the last updates (SI-Hex version march 2014 and related work of Denieul 2014; Benjumea et al., version October 2014).

The Mw comes mainly from Benjumea at al. (2014) results (SIGMA WP1) before 1962 and SI-Hex catalogue version march 2014 (MEDDE, CNRS, Universities, CEA) including Denieul (SIGMA WP1, label "SI-Hex2014 coda" in table 3) results after 1962. Theses Mw are considered as the reference values. The most constrained are deduced from the coda analysis (yellow in table 3)

The depth appears to be very poorly constrained despite all the works developed by the study of Benjumea et al. (SIGMA WP1) and the SI-Hex project (MEDDE, CNRS, Universities, CEA). The uncertainty on the depth is still very high due to the lack of near field seismic stations. The methods based on the waveform analysis to retrieve the depth, as Benjumea et al. (2014) for historical instrumental period (before 1962) or source inversion for recent event, do not bring to agreed values. Only few events have very precise depth estimation (yellow in table 3). Nevertheless, the depth obtained by Benjumea et al. (2014) is included as reference value.

Most of the events, 20 on the 22, are at a depth of less than 15 km and their magnitude is between 4.5 and 6.1 Mw (table 3, figure 18). The dataset is dominated by event with Mw between 4.9 and 5.5 with 17 events on the 22. They are mostly near the border of France limiting the azimuthal coverage for the available IDPs (Figure 17). Combining cross-border data would strongly improve the analysis (Cara et al. 2005, Cara et al. 2007 - Rambervillers).

Event name	Mw	Mw author	Depth	Depth author	SisFrance ID	Year	Month	Day	Epic. Int. MSK	IDP numbers	Lat	Long	Catalogue for loc.
Chamonix - Mont-Blanc	5.4	Benjumea oct2014	5	Benjumea oct2014	740060	1905	4	29	7.5	302	46.08	6.9	SisFrance oct-2014
Lambesc	5.8	Benjumea oct2014	10	Benjumea oct2014	130057	1909	6	11	8.5	475	43.65	5.32	SisFrance oct-2014
Jura Souabe	5.5	Benjumea oct2014	4	Benjumea oct2014	1110061	1911	11	16	8.5	480	48.28	8.93	SisFrance oct-2014
Val d'Aran	5.4	Benjumea oct2014	5	Benjumea oct2014	1140024	1923	11	19	8	652	42.7	0.83	SisFrance oct-2014
Kayserstuhl	5	Kunze 1986	15	Karnik 1969	1110017	1926	6	28	7	735	48.13	7.63	SisFrance oct-2014
Landes de Lanvaux	5.4	Benjumea oct2014	5	Benjumea oct2014	560027	1930	1	9	7	543	47.73	-2.8	SisFrance oct-2014
Embrunais	4.9	Benjumea oct2014	10	Benjumea oct2014	50043	1935	3	19	7	254	44.58	6.63	SisFrance oct-2014
Angoumois	4.9	EMEC 2012			160012	1935	9	28	7	647	45.77	-0.03	SisFrance oct-2014
Offenburg	4.6	EMEC 2012	30	Karnik 1969	1110076	1935	12	30	7	834	48.62	8.22	SisFrance oct-2014
Flandres (Belgique)	5.1	Benjumea oct2014	30	Benjumea oct2014	1100014	1938	6	11	7	1445	50.77	3.63	SisFrance oct-2014
Valais (Suisse)	5.8	Benjumea oct2014	5	Benjumea oct2014	1120028	1946	1	25	7.5	476	46.28	7.55	SisFrance oct-2014
Valais	5.5	Fritsche et al. 2012			1120033	1946	5	30	7	388	46.28	7.55	SisFrance oct-2014
Cornouaille	5.3	Benjumea oct2014	5	Benjumea oct2014	290030	1959	1	2	7	784	47.93	-4	SisFrance oct-2014
Ubaye	5.1	Benjumea oct2014	10	Benjumea oct2014	40109	1959	4	5	7.5	207	44.53	6.82	SisFrance oct-2014
Vercors	5.5	SI-Hex2014	6	Benjumea oct2014	380070	1962	4	25	7.5	506	44.95	5.4	SI-Hex2014
Mer Ligure-Imperia	6.1	Benjumea oct2014	6	Benjumea oct2014	1130086	1963	7	19	7	410	43.34	8.12	SI-Hex2014
Arette	5.2	SI-Hex2014 coda	3	Benjumea oct2014	640362	1967	8	13	8	839	43.19	-0.68	SI-Hex2014
Oléron	5	SI-Hex2014 coda	11	SI-Hex2014 LDG	170079	1972	9	7	7	446	45.98	-1.49	SI-Hex2014
Piemont (Italie)	4.5	SI-Hex2014	10	SI-Hex2014 LDG	1130135	1980	1	5	7	491	44.95	7.45	SI-Hex2014
Ossau	5	SI-Hex2014 coda	5.4	SI-Hex2014 OMP	640001	1980	2	29	7.5	1323	43.07	-0.4	SI-Hex2014
Annecy	4.9	SI-Hex2014 coda	3	SI-Hex2014 GRN	740153	1996	7	15	7	782	45.93	6.1	SI-Hex2014
Rambervillers	4.9	SI-Hex2014 coda	12	LDG	BCSF	2003	2	22	6.5	5212	48.37	6.64	SI-Hex2014

Table 3: List of event analysed and associated parameters. The numbers underlined by yellow colour are the most constrained values.

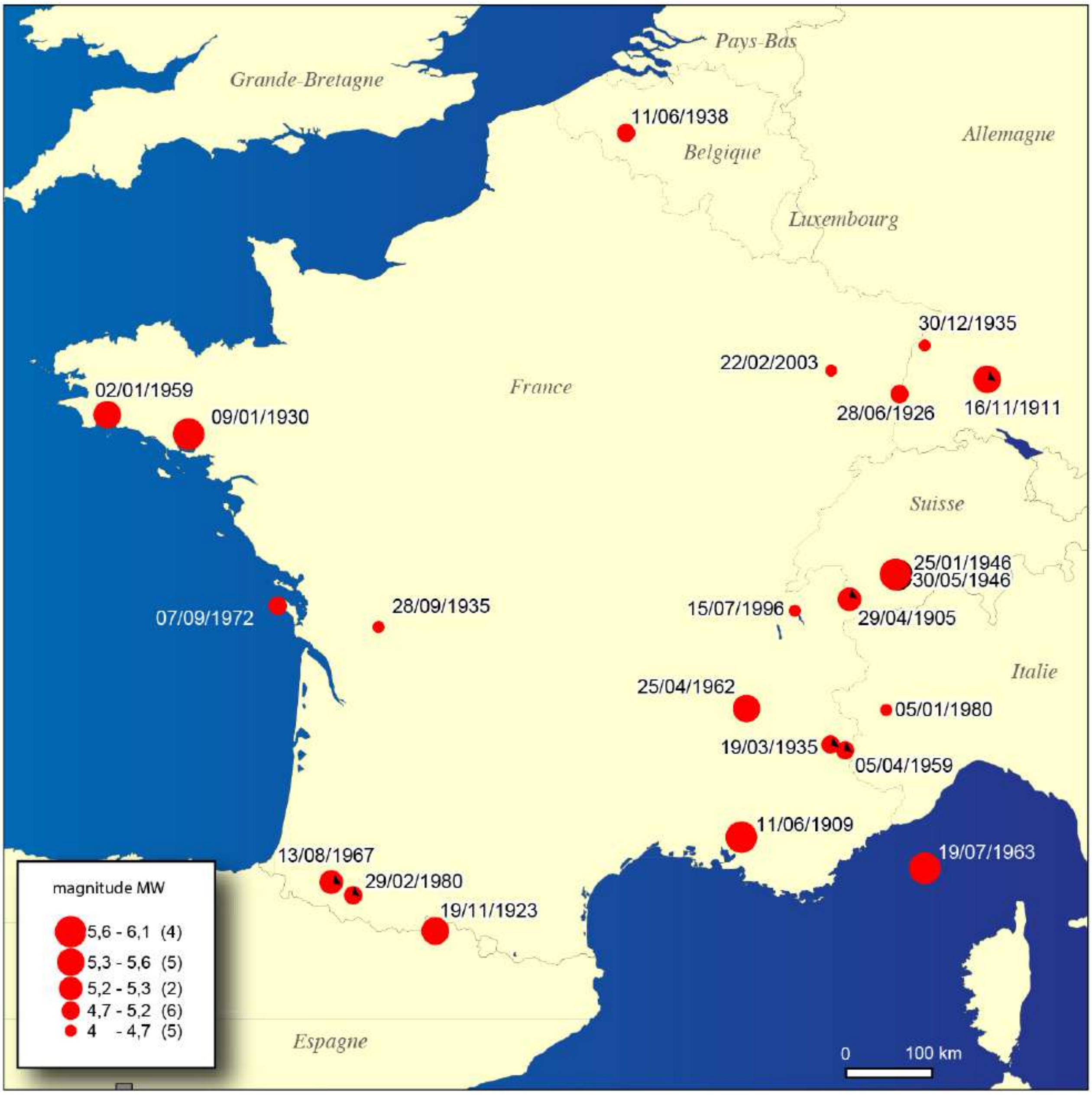


Figure 17: Location of the earthquakes analysed in this study.

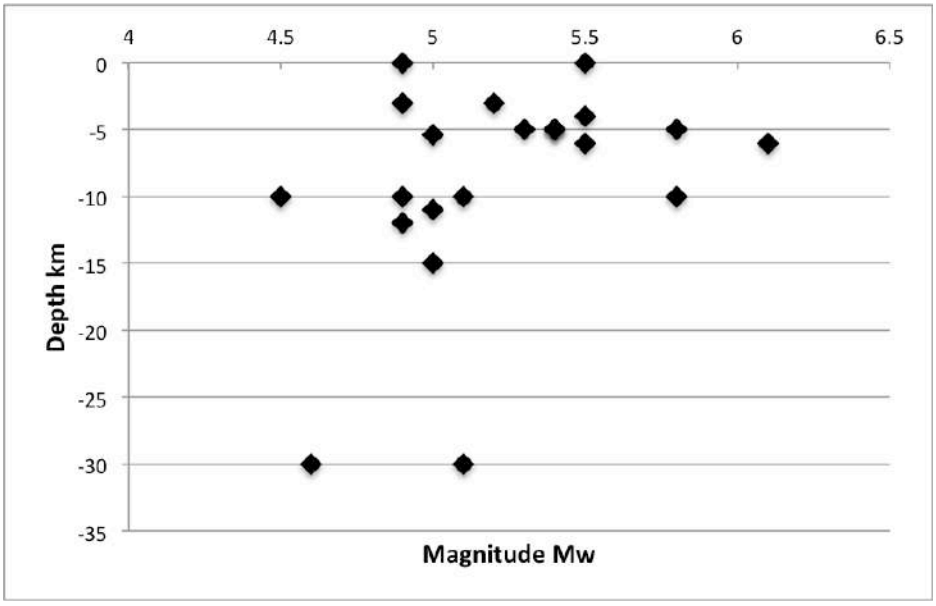


Figure 18: Depth versus magnitude for the events analysed in this study.

Mapping of the selected events

An atlas of 88 maps (annexe 3) represents the results of the Kriging methods applied to the 22 events selected in the XXth century. For each of them, we present 4 maps: the IDPs, the interpolation by kriging, the IDPs overlying the kriging interpolation to see the accuracy of the result and the kriging interpolation with the isoseismals.

For each of them, the title gives the date of the event, the common name associate, Mw, Depth and the minimal Intensity of the constrained isoseismal by the kriging interpolation. The minimal intensity will be explained and detailed here under.

Following the criteria and parameters we use for the kriging, the interpolation/extrapolation is not calculated if they are not respected. This induces discontinuous interpolation and mapping.

The isoseismals correspond to the change in the integer values of the Intensity; no any smoothing is applied on calculated values.

Isoseismal surfaces

The isoseismals surfaces are calculated with 0.1 steps in Intensity. It allows better describing the intensity variation as the kriging induce interpolated values following the variogram model.

After converting the surface in “equivalent surface radius”, we plot them versus the intensity. Nevertheless, we can easy observe that, in most cases, only the highest isoseismals are completed (Annexe 3). The reason is that most of the events are near natural borders (shore line) or France border and that foreign data are not included in the datasets. It is obvious that cross-border mapping, as done for the Rambervillers earthquake, would strongly improve the processing and results.

Therefore, to avoid misinterpretation, **we limited the plot to the complete isoseismals**. It reduces generally the "equivalent surface radius" at less than 100km and the intensities to value higher than IV or V. The extreme case is for events for which we do not have data starting from epicentre area (as the 16-11-1911 Jura Souabe earthquake) and for which we will not apply our procedure. The minimum intensity used is reference for each earthquake in the annexe 3. **This implies that there is no any relation between the total number of the IDP of a dataset and the possibility to calculate equivalent surface radius.** We must have enough data in the epicentre area and around it, with at least a variation of 3 intensity degrees. Without them far dense IPD are useless for our purpose (not useful for depth analysis).

For the Oléron earthquake of 1972, the geometry of the cost induced that only about 180° are covered, the complementary being in the Atlantic Ocean. Due to this particular situation, we multiplied the total observation surfaces by 2 considering a hypothesis of symmetry in the radiation. It is probably acceptable at the first order and must be kept in mind for the interpretations.

Isoseismal surfaces versus magnitude and depth

All the surfaces and associated equivalent surface radius are calculated with the same kriging procedure and parameters. The only variation is the variogram model that has to be fitted with the data of each event. Therefore, we can compare the radius decay with distance for all the events.

First of all, the comparison of all the data shows that outside the 1972 Oleron event, we are limited to 100 km radius (figure 19 and 20).

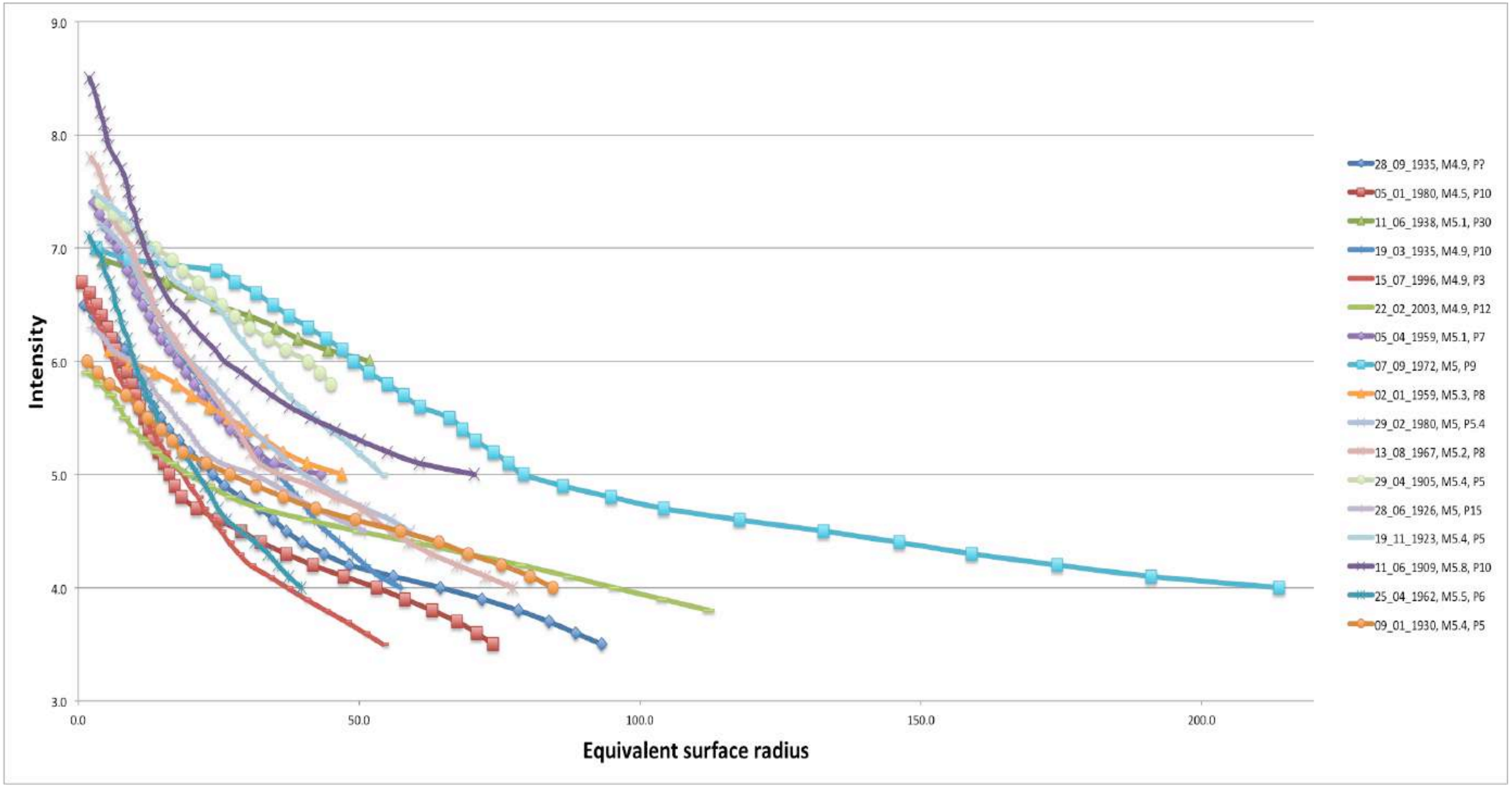


Figure 19: Plot of all events studied. The magnitude and depth (P) in the legend are those given by instrumental analysis (Denieul 2014 – SI-Hex2014 – Benjumea et al. 2014)

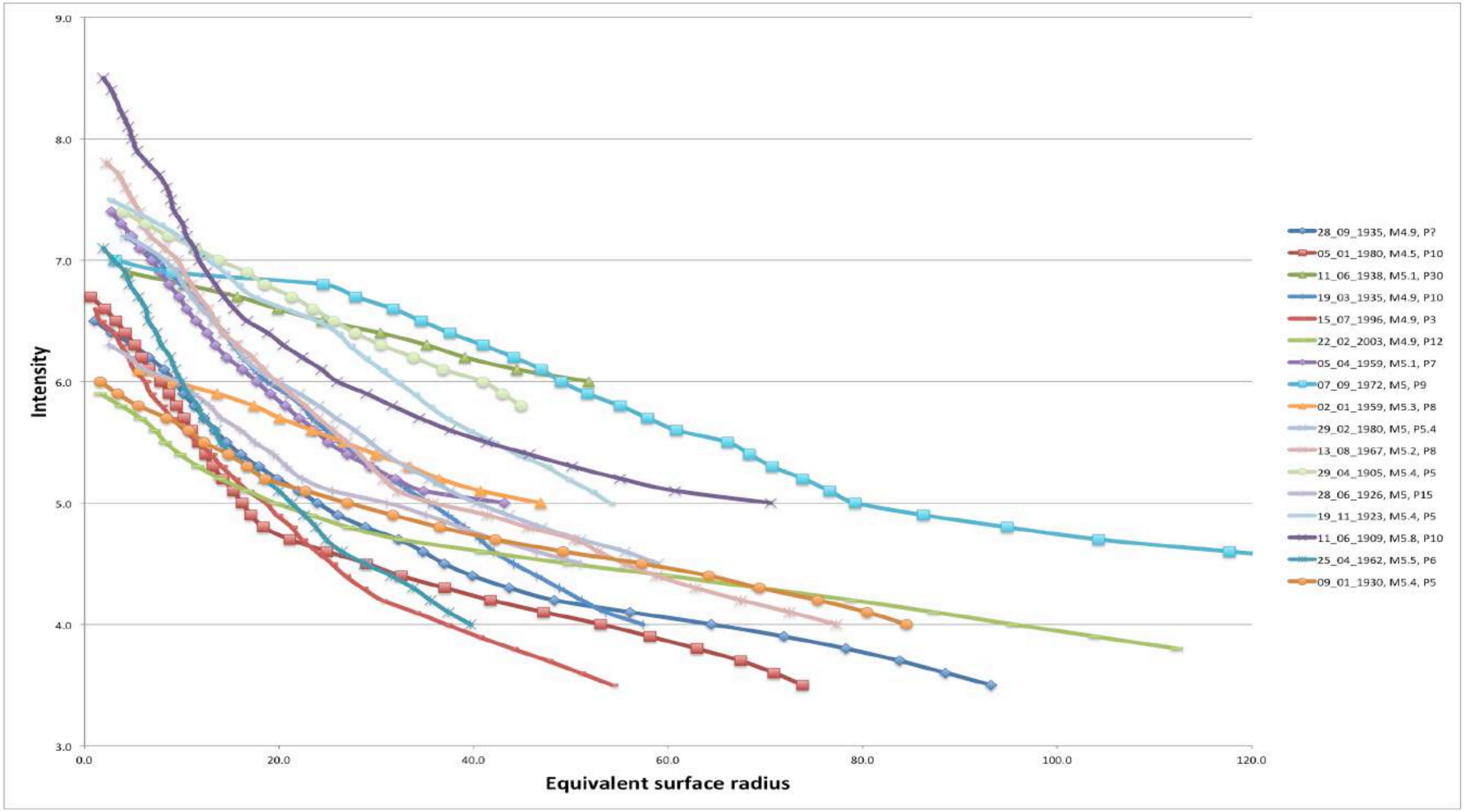


Figure 20: Plot up to 120 km of all event studied. The magnitude and depth (P) in the legend are those given by instrumental analysis (Denieul 2014 – SI-Hex2014 – Benjumea et al. 2014)

Two slopes for each event are obvious. The shortest radiuses represent the impact of the depth; more steep is the slope shallower is the hypocentre. The longest radiuses show a second slope, which are not any more impacted by the depth but characterises the magnitude. This magnitude slope is not the same for each event and is probably related to the various regional attenuation laws (Bakun and Scotti 2006) (Figure 21).

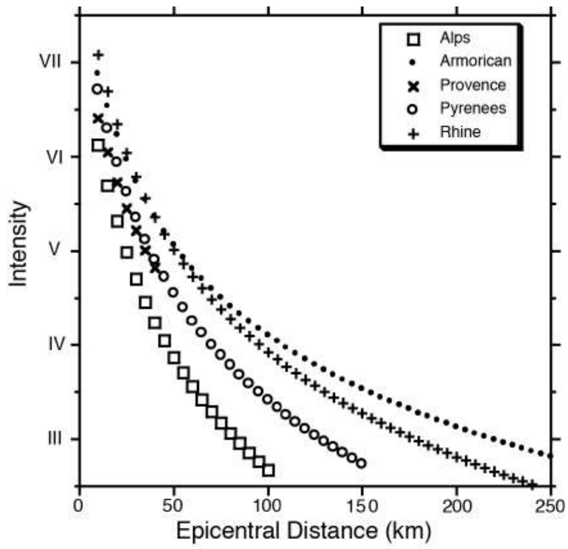


Figure 21: Intensity attenuation models for an M 5.0 source at 10 km depth in the French Alps, Armorican, Provence, Pyrenees and Rhine regions. (Bakun-Scotti 2006).

Comparing all the data, we see several events that have very similar slope either at short or long distance radius. In the next part of the chapter, we will discuss in details the parameters (Mw and depth) that could be deduced from various plots.

Comparison of earthquakes since 1962 with SI-Hex catalogue parameters

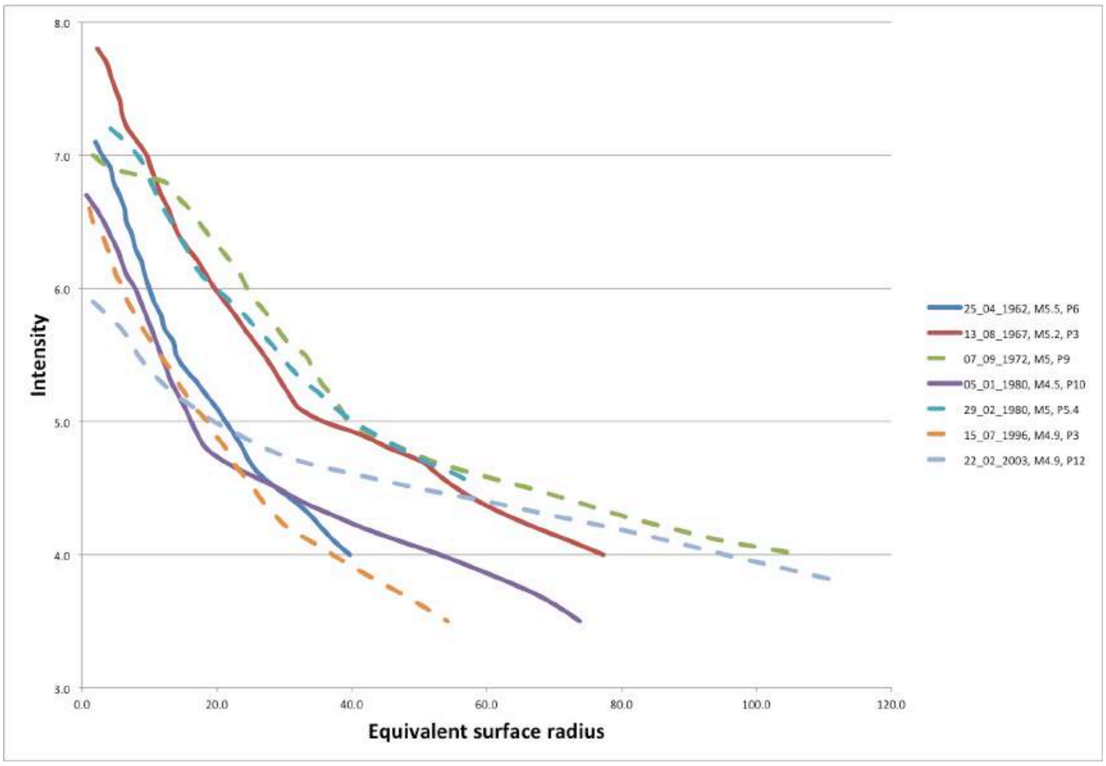


Figure 22: comparison between earthquakes since 1962 (SI-Hex period)

The Mw is well constrained over the period concerned by the "national reference catalogue" produced by the SI-Hex project (1992-2009) (Cara et al. 2015, Denieul et al. 2015). For the events since 1962 analysed, the Mw estimation is better for the 13/08/1967, 07/09/1972, 29/02/1980, 15/07/1996 and 22/03/2003 events and the depth is well constrained for the 29/02/1980, 15/07/1996 and 22/03/2003 events.

We see clearly in figure 22 that the hierarchy for the depth is respected with short distance slope getting steeper when the depth decreases (from deep to shallow: 22/03/2003, 29/02/1980 and 15/07/1996). Our procedure gives results that appear very consistent with constrained instrumental depth parameter.

For the long distance slopes, which characterise the magnitude, we see clearly that the slopes are not parallel making impossible a direct comparison. Nevertheless, if we separate the datasets by regions, we see that the long distance slope of the 15/07/1996 and 25/04/1962 (Alps) or the 29/02/1980 and 13/08/1967 (Pyrenees) or 22/03/2003 and 07/09/1972 (Rhine-Armorica) are similar and that the Italian 1980 event has a particular behaviour. We see here an illustration of the various regional attenuations (Bakun and Scotti 2006). Therefore the analysis of the event will be done later separately for each region.

Comparison of earthquakes with 4.5 ≤ Mw ≤ 4.9

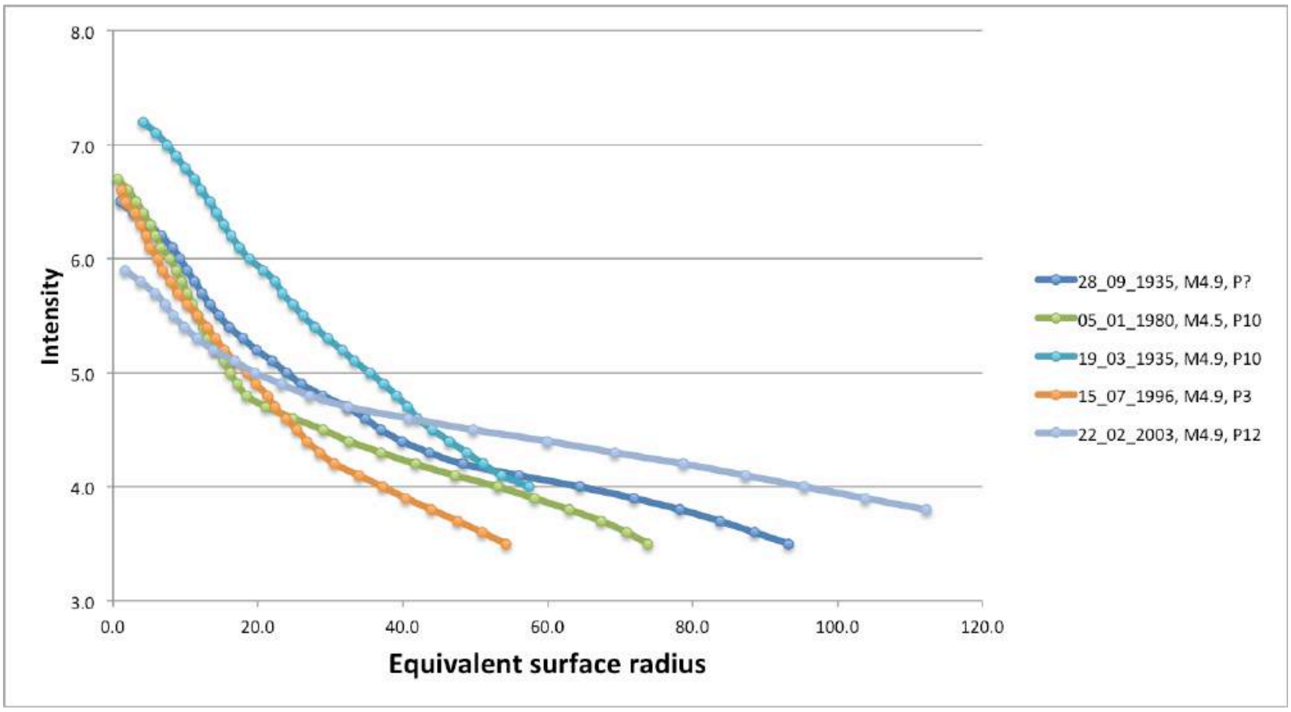


Figure 23: Comparison of earthquake with Mw between 4.5 and 4.9.

- The most constrained events are the 2003 Rambervillers (depth 12 km, Mw=4.9) and the 1996 Annecy (depth 3km, Mw=4.9) earthquakes.
- The 2003 event is the deepest, about 12 km, confirmed by a gentle slope at short distance.
- The 1980 and 1996 have similar short distance slope suggesting a much shallower depth than 10km for the 1980 one.
- The long distances slopes are variable due to the location of the events in various regions (Rhine for 2003, Alps for 1996 and 19/03/1935, south Armorica for 28/09/1935, Italy for the 05/01/1980) making impossible to compare their magnitude.

Notice that the 1980 event is outside SI-Hex catalogue area (one of those outside SI-Hex but with induced intensity of IV or more in France) but the magnitude has been calculated in the SI-Hex project with a conversion between ML (LDG) and Mw based on the results of Denieul (2014) and Denieul et al. (2015) (Coda Mw). The depth of 10 km is provided by the LDG for this event (preferential location chosen between those of French observatories.

Comparison of earthquakes with 5 ≤ Mw ≤ 5.4

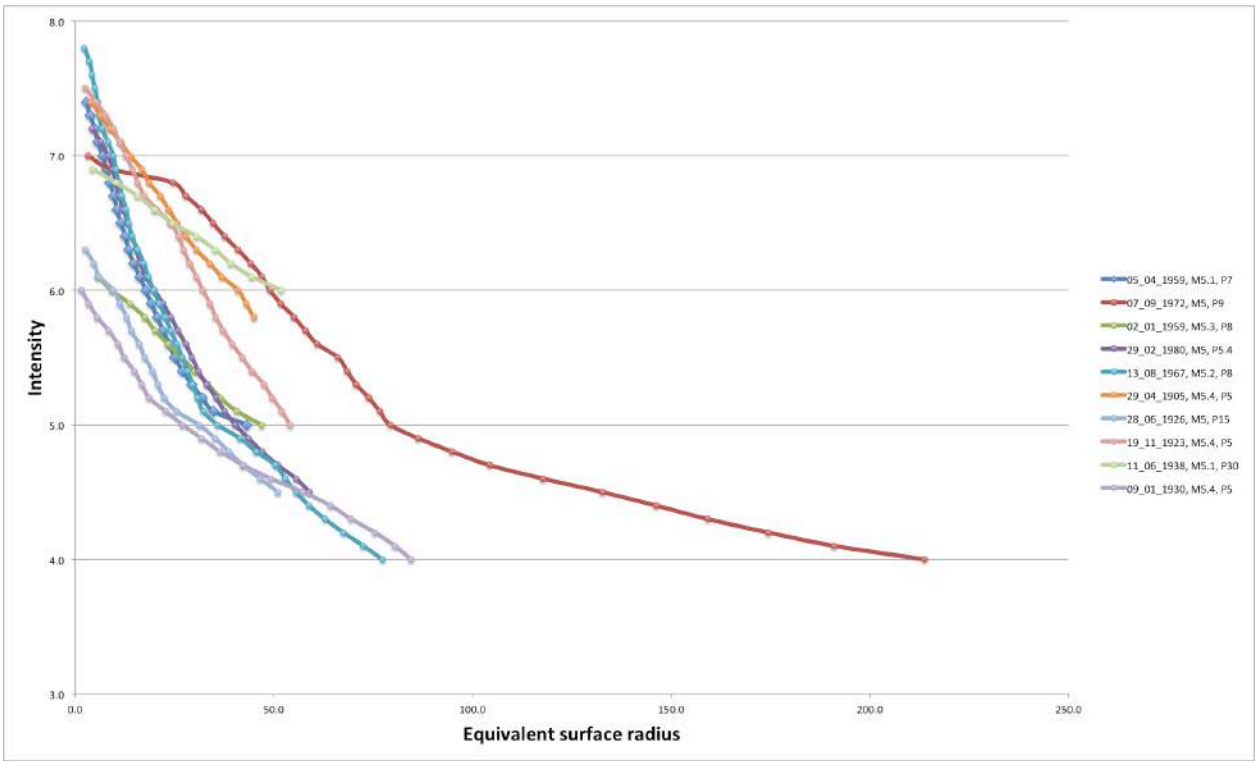


Figure 24: Comparison of earthquake with Mw between 5 and 5.4 up to 220 km.

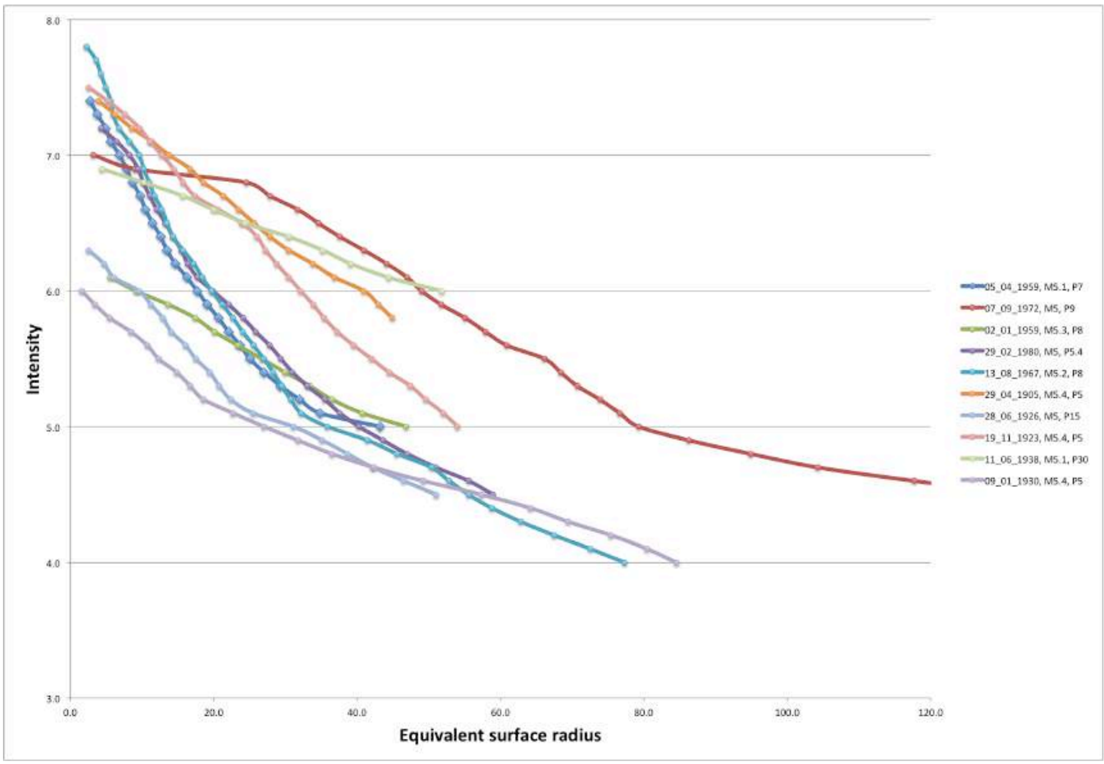


Figure 25: Comparison of earthquake with Mw between 5 and 5.4 up to 120 km.

The 1938 event has a very gentle slope for short distance indicating a deep event as proposed by the Belgium observatory (19km) or even deeper (about 25 km, Camelbeeck personal communication). It shows the lowest slope of all the studied datasets indicating a much deeper hypocentre than 12 km proposed by Benjumea et al. 2014.

The 1938 event shows also the highest level of intensity at 60 km of all the studied datasets (VI) indicating that its magnitude is probably the highest.

The long distances slopes are variable due to the location of the events in various regions (Rhine for 2003, Alps for 1996, south Armorica for 28/09/1935) making impossible to compare their magnitude.

Comparison of earthquakes with 5.4 ≤ Mw ≤ 5.9

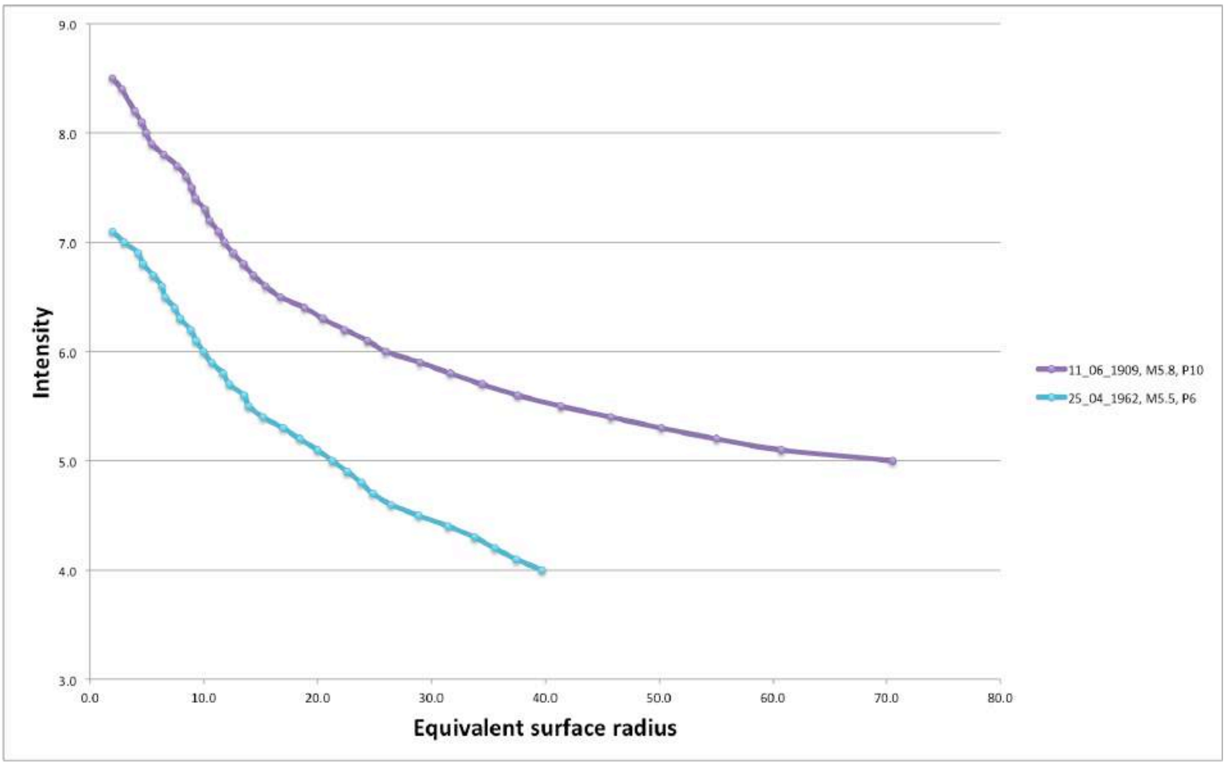


Figure 26: Comparison of earthquake with Mw between 5.5 and 5.9.

The long distances slopes are variable due to the location of the events in various regions (Provence for 1909, Alps for 1996) where attenuation is very different (Bakun and Scotti 2006). Nevertheless, the hierarchy, with 1909 event greater than 1962, is clear.

Comparison of the two 1946 Valais earthquakes

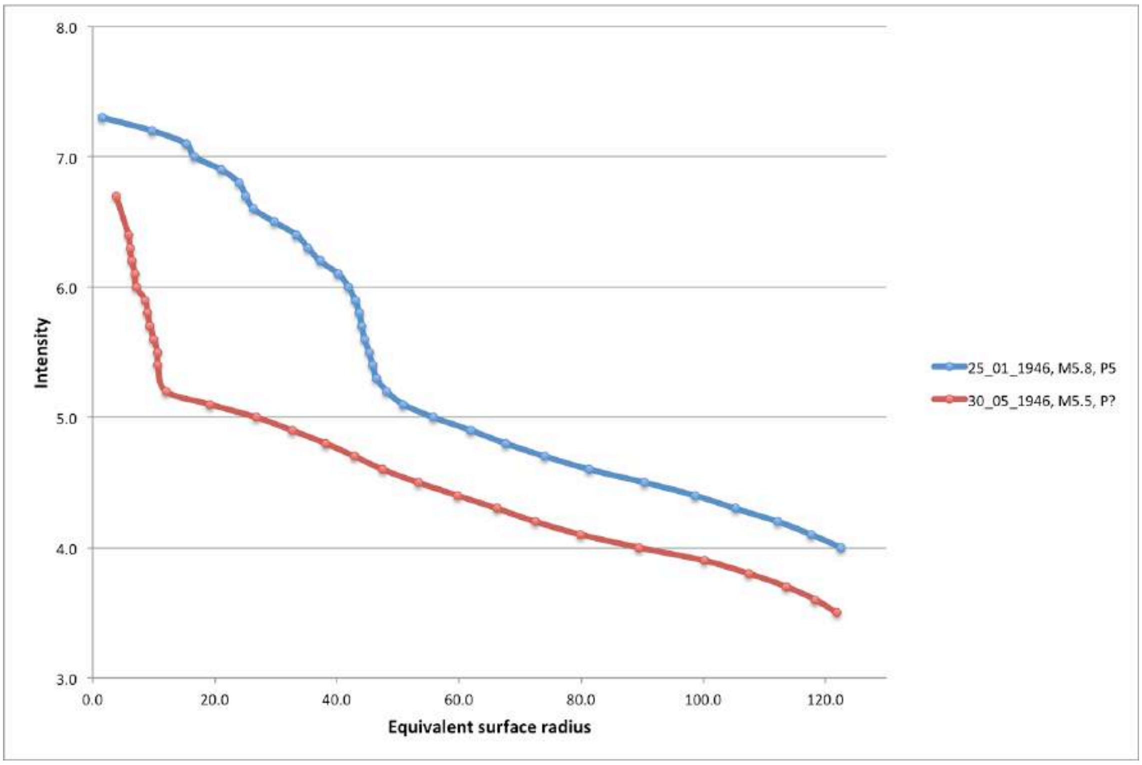


Figure 27: Comparison between the two Valais earthquakes of 1946.

We did not use these two events in the previous comparisons as we have incomplete information in the epicentre area and none of the isoseismals are complete. In that case, the "equivalent surface radius" does not represent a view of the regional attenuation. Nevertheless, du to their close location, the areas with macroseismic data are comparable if we consider only the equivalent surface radius of more than 50km (figure 27). The slopes are equivalent and their intensity differences exhibit the magnitude variation.

Cara at al. 2008 proposed a relation between ΔI and ΔMw as: ΔI = 2.22 ΔMw.

Mw comparison of 1946 events: We observe between the two events a ΔI of 0.5 that gives a ΔMw of about 0.23, value consistent with the analysis of Benjumea et al. 2014 (ΔMw=0.3). The lack of information in epicentre area forbids any interpretation for the depth.

Comparison of Alps earthquakes

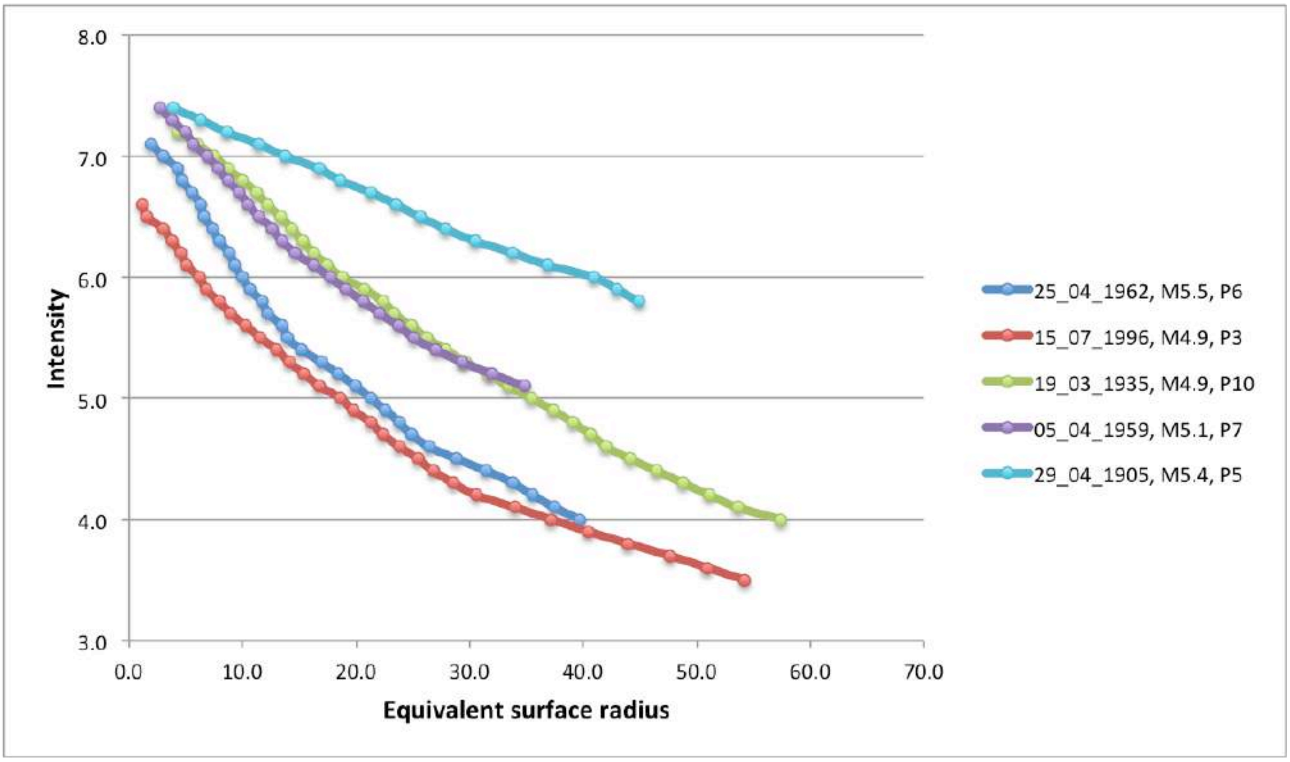


Figure 28: Comparison between the earthquakes in Alps.

The 1996 earthquake hypocentre is very precisely located by the Sismalp network (SI-Hex 2014 with Grenoble observatory preferential location).

Depth of 1962 event: We see obviously that the Vercors event of 1962, for which we have poor instrumental information, has a short distance slope steeper that the 1996 indicating a very shallow hypocentre, probably shallower than 3km, clearly shallower than the 6km proposed instrumentally.

Mw of 1962 event: Also the difference in magnitude calculated by Benjumea et al. 2014 (Mw=5.5) or by the SI-Hex 2014 catalogue (empirical relation between $M_{L\text{-}LDG}$ and Mw) is not consistent with the macroseismic observations of the two events. The 1962 Vercors event is just over and very close to the 1996 event, with a difference probably of less than 0.1 in magnitude. A part of its overestimation in magnitude from instrumental data could be due to an overestimation of its depth.

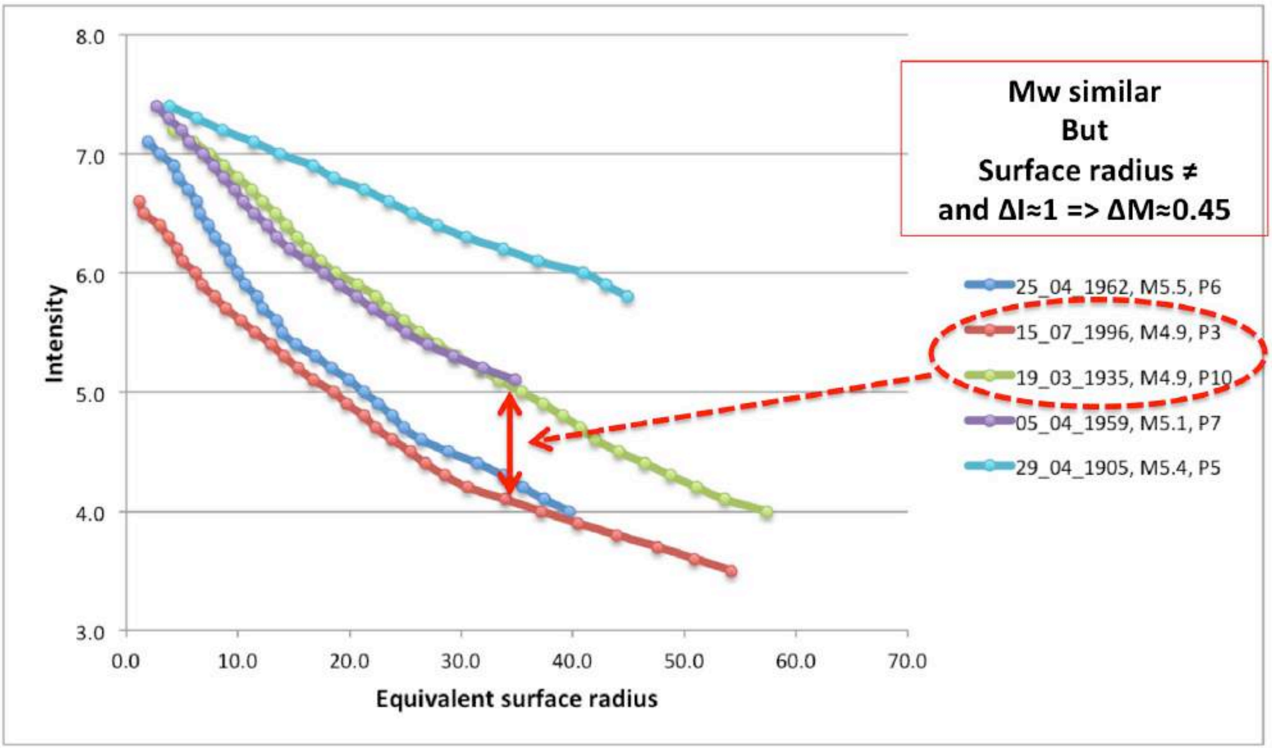


Figure 28b: Comparison between the earthquakes in Alps.

Depth of 1935 and 1959 events: The isoseismals area of the 1935 event is very close those of the 1959 event. At short distance, their slope are also similar to 1996 Annecy event suggesting a very shallow hypocentre.

Mw of 1935 and 1959 events: The ΔI with 1996 event is about 1 giving a ΔMw of about 0.45. Their magnitude would then be 5.3 to 5.4 (figure 28b).

Is it possible to compare the 1935, 1959 and 1996 events considering the different number of IDPs for 1935 (254 IDP), 1959 (207 IDP) and 1996 (782 IDP)? First, we have to consider that we use only isoseismals at less than 35 km for the 1959 event when we consider about 55km for the 1935 and 1996. This limitation is due to the lack of information to build constrained isoseismals at greater distance. Therefore, the initial number of IDP is not a parameter quantifying the quality of the result. When we look more in details the datasets of these 3 events, we see that even for the 1996 earthquake, there is a very low local variability of intensity. Therefore, the possible impact of the reduced dataset for the 1935 and 1969 events for an overestimation of the isoseismals area is not likely. This is also supported by another observation: The slopes at long distance are similar when it should decrease when such artefact appears. The similar slope at regional distance reveals the regional attenuation.

Mw and depth of 1905 event: The 1905 events could be characterised only for short radius. Therefore, we have no constrain on its magnitude. Its short distance slope is much gentler than the other Alps event indicating a deeper event, but without deep event as reference event (with good constrain on its depth) we can only suggest that it is much deeper than 3 km.

Comparison of Pyrenees earthquakes and Lambesc 1909 (Provence)

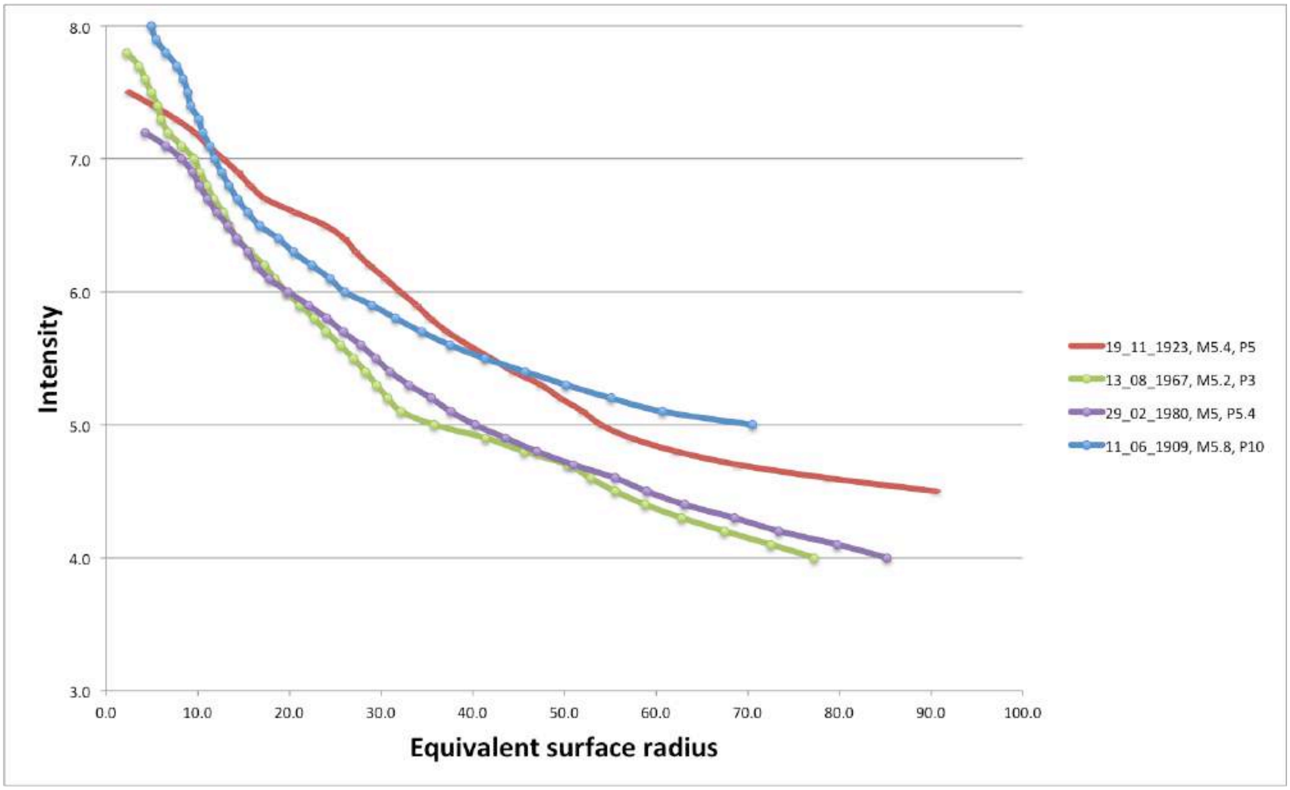


Figure 29: Comparison between the earthquakes in Pyrenees and Lambesc 1909.

Mw of 1980 event: The 1980 event has hypocentre (SI-Hex2014, OMP) and Mw (Mw coda SI-Hex 2014) well constrained. The 1980 event Mw (Mw coda SI-Hex 2014) is 0.2 lower than 1967 while the isoseismals area curves are very similar. Nevertheless, the 0.2 variations in Mw or the distance between the two curves are within uncertainties of the instrumental and macroseismic methods.

Depth of 1980 event: The 1996 event short distance slope is steeper than the 1980, consistent with a shallower depth of about 3 km as proposed by Benjumea et al. 2014.

Mw of 1923 event: For the Mw, the slope of the 1923 event is also gentler, which either indicates a different attenuation between eastern and western part of Pyrenees or that the IDPs of 1923 represent only the highest value that would increase the isoseismal areas. This event is characterised by a large set of IDPs (652) but with the highest density of data concentrated in only one department the “Haute Pyrénées”. The ΔI with 1980 or 1967 is about 0.5 giving a ΔMw of 0.23 consistent with the proposed value by Benjumea et al. (2014).

Depth of 1923 event: For the 1923 event, the short distance slope is gentler than the 1996 or 1980 events indicating a deeper hypocentre than the one proposed in the Benjumea et al. (2014) analysis. Without deeper reference event in the area, we cannot propose depth value.

The 1909 event is compared to those of Pyrenees, as the attenuation relations are similar in those two regions (Bakun and Scotti, 2006).

Depth of 1909 event: We observe first that the short distance slope is comparable to those of the 1967 and 1980 events suggesting a shallow hypocentre for the 1909 Lambesc event, probably about 5km.

Mw of 1909 event: For the magnitude, the hierarchy is respected with for the lowest the 1967 and 1980 events, then the 1923 and then the highest magnitude for the 1909 earthquake. If we compare the 1980 well-constrained event and the 1909 at 40km radius, we have ΔI=0.5 giving ΔMw 0.23 while at 70 km we have a ΔI=0.7 giving a ΔMw of 0.3.

From our procedure, we would propose a magnitude of about Mw=5.3 and a depth of about 5 km. If the short distance slope is well constrained (depth), the long distance could be affected by incomplete spatial coverage of IDP as we can see on the maps (Annexe 3) but in that case the real magnitude should be still lower. Nevertheless, a ΔMw of 0.8 as proposed by Benjumea et al. 2014 should imply a ΔI of about 1.7, which is totally not consistent with of the results based on SisFrance data and our procedure.

Comparison of the 1926 and 2003 earthquakes (NE France)

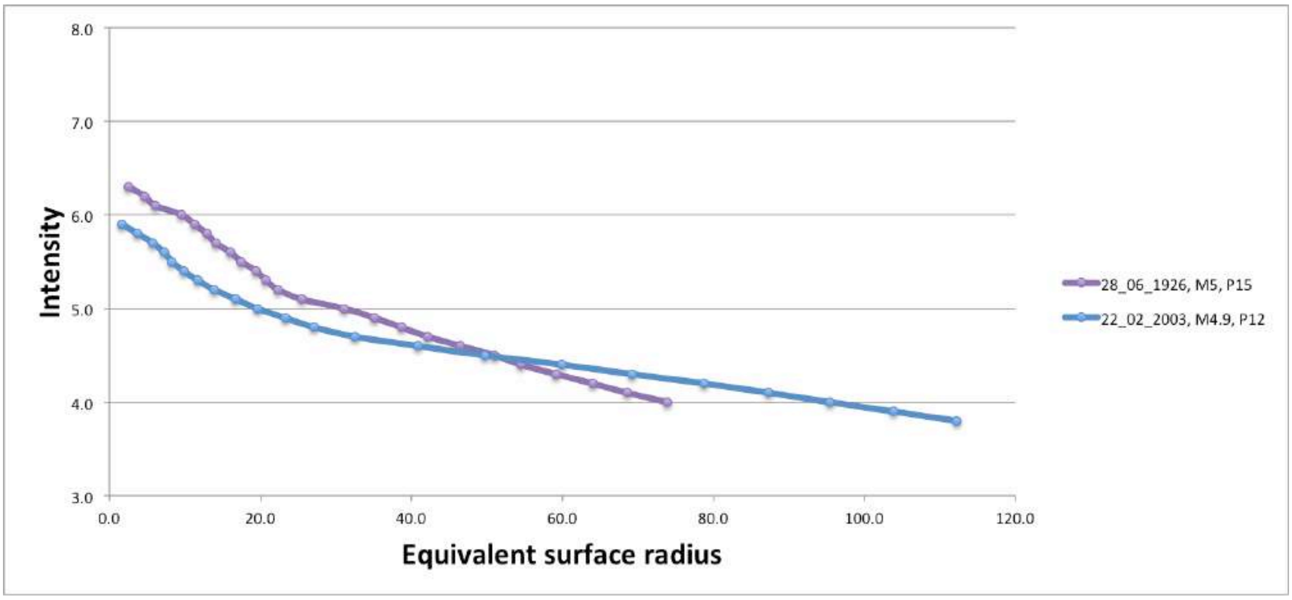


Figure 30: Comparison of the 1926 and 2003 earthquakes.

Depth of the 1926 event: The 1926 event shows very similar short distance slope to the 2003 event, which is well constrained. The equivalent surface radius for 1926 deduced from macroseismic observations are consistent with the 15 km deep hypocentre proposed by Benjumea et al. (2014).

Mw of the 1926 event: The ΔI at short distance is about 0.3 giving a ΔMw of 0.14 also consistent with the Mw proposed by Benjumea et al. (2014).

Comparison of the Armorica and 2003 (NE France) earthquakes

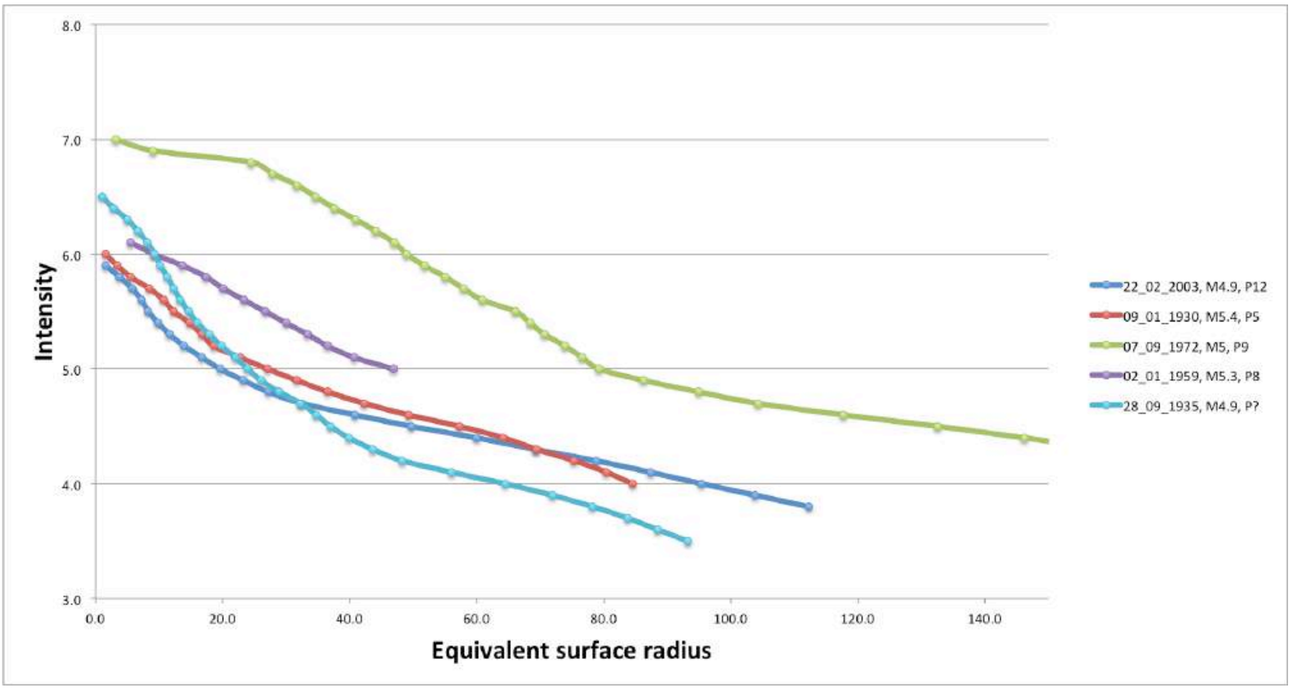


Figure 31: Comparison between the earthquakes of Rambervillers (2003) and Armorican events.

The attenuation relations of these two regions are very similar (Bakun et Scotti, 2006) allowing us to use the 2003 Rambervillers earthquake as reference event for the Armorica area

Mw and depth of 1930 event: The 2003 and 1930 events are similar indicating a much smaller magnitude for the 1930 event (about Mw=5) and a deeper hypocentre (about 12 km) than the values obtained by Benjumea et al. (2014). Such differences as obtained by Benjumea et al. 2014 (0.5 in magnitude and 7 km in depth) if real should be obvious on the macroseismic data and the curves.

Mw of Armorica events: The hierarchy in magnitude should be (low to high): 1935, 2003, 1930, 1959 and 1972.

1935 = 2003 or 1935 = 1930 – 0.13 to 0.23 => **Mw≈ 4.7**
1930 = 2003 => **Mw ≈ 4.9**
1959 between 2003 and 1972. => **Mw ≈ 5 – 5.1**
1972= 2003 or 1972=1930 + 0.36=> **Mw≈ 5.3**

Depth of Armorica events: The hierarchy in depth should be (deep to shallow): 1959,1972, 1930, 2003 and 1935. All Armorica events should be deeper than 12 km except the 1935 that is shallower, probably about 5km.

Macroseismic Mw and depth using Master events and isoseismals area

Macroseismic Mw and depth using Master events and isoseismals area has been used in the past by Cara et al. (2008). They noticed "**To avoid the uncertainties due to the attenuation law, site effects, or shift in frequency with epicentral distance, Cara et al. (2005) have proposed to compare directly the intensities of a recent instrumentally-known earthquake with the historical-earthquake intensities at large distances from the epicentre**".

This proxy has been used by Cara et al. (2008) but only for the magnitude. Their approach was simpler as they did not work on the depth of the event. They calculated the intensity at a specific distance as "equal to the average of observed intensities", which is not really characteristic of the isoseismal surface.

In the table 4 we summarise the result deduced from our procedure for the studied earthquakes. The values in red are the Mw with a difference of 0.4 or more with the value proposed (left side of the table) or with an important difference in the depth.

Event name	Year-month-day	Mw	Mw author	depth	depth author	Mw macro (this study)	ref event	Depth Macro (This study)	ref event
Chamonix - Mont-Blanc	1905-4-29	5.4 5.1 – 5.7	Benjumea oct2014 Manchuel et al. 2015	5	Benjumea oct2014	unknown		>> 3 km	1996-7-15
Lambesc	1909-6-11	5.8 `5.5 - 6.1	Benjumea oct2014 Manchuel et al. 2015	10	Benjumea oct2014	+0.3 => Mw 5.3	1980-2-29	about 5 km	1980-2-29
Jura Souabe	1911-11-16	5.4 5.2 - 5.6	Benjumea oct2014 Manchuel et al. 2015	4	Benjumea oct2014	unknown		unknown	
Val d'Aran	1923-11-19	5.4 5.2 – 5.7	Benjumea oct2014 Manchuel et al. 2015	5	Benjumea oct2014	+0.2 => Mw 5.2	1980-2-29	> 5.4	1980-2-29
Kayserstuhl	1926-6-28	5	Kunze 1986	15	Karnik 1969	+0.1 => Mw 5	2003-2-22	about 12	2003-2-22
Landes de Lanvaux	1930-1-9	5.4 4.8 – 5.3	Benjumea oct2014 Manchuel et al. 2015	5	Benjumea oct2014	equal => Mw 4.9	2003-2-22	about 12	2003-2-22
Embrunais	1935-3-19	4.9 4.5 – 5.3	Benjumea oct2014 Manchuel et al. 2015	10	Benjumea oct2014	+0.35 => Mw 5.3-5.4	1996-7-15	about 3 km	1996-7-15
Angoumois	1935-9-28	4.9	EMEC 2012			-0.2 => Mw 4.7	2003-2-22 & 1930-1-9	<12 (about 5 km?)	2003-2-22
Offenburg	1935-12-30	4.6	EMEC 2012	30	Karnik 1969	unknown		unknown	
Flandres (Belgique)	1938-6-11	5.1 4.5 – 5.5	Benjumea oct2014 Manchuel et al. 2015	30	Benjumea oct2014	Mw > 5.3	2003-2-22 & 1972-9-7	>> 12km	2003-2-22
Valais (Suisse)	1946-1-25	5.8 5.1 – 5.7	Benjumea oct2014 Manchuel et al. 2015	5	Benjumea oct2014	+0.23 => Mw 5.7 - 5.8 (relative, no ref event)	1946-5-30	unknown	
Valais	1946-5-30	5.5	Fritsche et al. 2012			-0.23 => Mw 5.5 - 5.6 (relative, no ref event)	1946-1-25	unknown	
Cornouaille	1959-1-2	5.3 5 – 5.7	Benjumea oct2014 Manchuel et al. 2015	5	Benjumea oct2014	4.9 < Mw < 5.3 (about 5.1)	2003-2-22 & 1972-9-7	> 12 km	2003-2-22
Ubaye	1959-4-5	5.1 5 - 5.4	Benjumea oct2014 Manchuel et al. 2015	10	Benjumea oct2014	+0.35 => Mw 5.3-5.4	1996-7-15	about 3 km	1996-7-15
Vercors	1962-4-25	5.5 4.9 – 5.6	SI-Hex2014 Manchuel et al. 2015	6	Benjumea oct2014	+0.1 => Mw 5	1996-7-15	< 3km	1996-7-15
Mer Ligure- Imperia	1963-7-19	6.1 5.8 – 6.2	Benjumea oct2014 Manchuel et al. 2015	6	Benjumea oct2014	unknown		unknown	
Arette	1967-8-13	5.2 4.8 – 5.2	SI-Hex2014 coda Manchuel et al. 2015	3	Benjumea oct2014	5.2	ref	about 5 km	1980-2-29
Oléron	1972-9-7	5 5 – 5.4	SI-Hex2014 coda Manchuel et al. 2015	11	SI-Hex2014 LDG	+ 0.4 => 5.3	2003-2-22		
Piemont (Italie)	1980-1-5	4.5	SI-Hex2014	10	SI-Hex2014 LDG	unknown		about 3 km	1996-7-15
Ossau	1980-2-29	5	SI-Hex2014 coda	5.4	SI-Hex2014 OMP	5	ref	5.4	ref
Annecy	1996-7-15	4.9	SI-Hex2014 coda	3	SI-Hex2014 GRN	4.9	ref	3	ref
Rambervillers	2003-2-22	4.9	SI-Hex2014 coda	12	LDG	4.9	ref	12	ref

Table 4: Mw and Depth versus Master events using Isoseismals area analysis. The values in red are the Mw with a difference of 0.4 or more with the value proposed (left side of the table) or with an important difference in the depth (see that last data from Manchuel et al. 2015 always reduce the difference with our results).

Comparison between Levret et al 1994 and Bakun and Scotti 2006.

One of the differences between Levret et al 1994 and Bakun and Scotti 2006 is the separation between different regions characterised by different attenuations. In Bakun and Scotti 2006, they separated France into 5 regions: Rhine, Armorica, Provence, Pyrenees and French Alps (FA). The regions Rhine and Armorica (R-A) or Provence and Pyrenees (P-P) could be grouped, as their differences are very limited. The attenuation increases from R-A, through P-P until FA. A comparison between events of the same “attenuation region” is then necessary to avoid misinterpretation.

Notice that the attenuation relation of Levret et al. 1994 fits with Bakun and Scotti 2006 for Provence region for Mw=5 and depth 10km. If we change the magnitude, the fit is then better with other region (Mw=5.5 => better fit with R-A region, Mw=5 => better fit with P-P region, Mw=4.5 => better fit with FA region) (Figure 32 and 33)

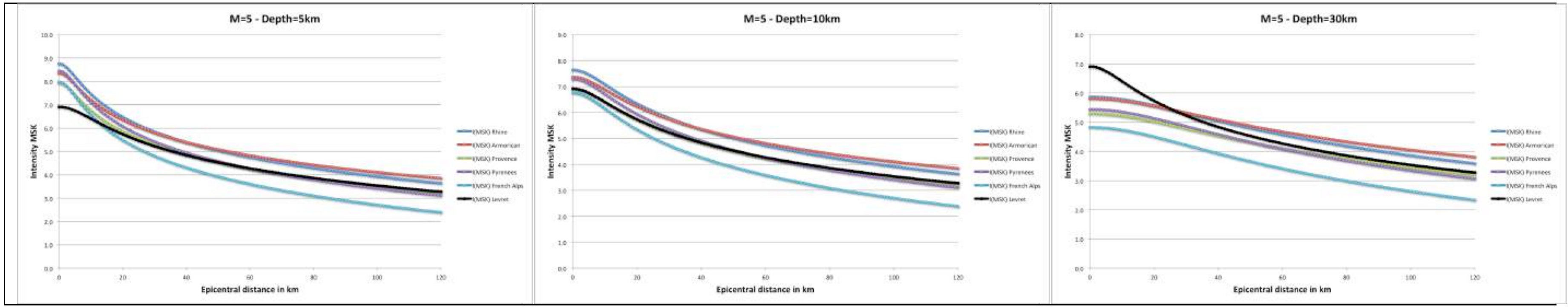


Figure 32: Comparison between Levret et al. 1994 and Bakun and Scotti 2006 for depth from 5, 10 and 30 km (Mw=5).

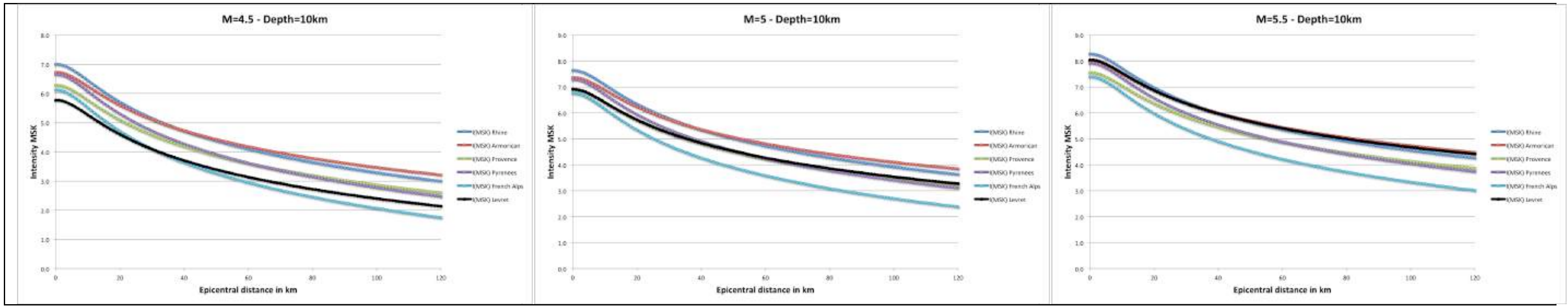


Figure 33: Comparison between Levret et al. 1994 and Bakun and Scotti 2006 for magnitude 4.5, 5 and 5.5 (depth 10 km).

Few comparison between regional observations and Bakun and Scotti 2006

Here under, we will compare the Bakun and Scotti relation (2006) for each region (Provence-Pyrenees, Rhine-Armorica, Alps) using an average Mw and Depth for the associated datasets.

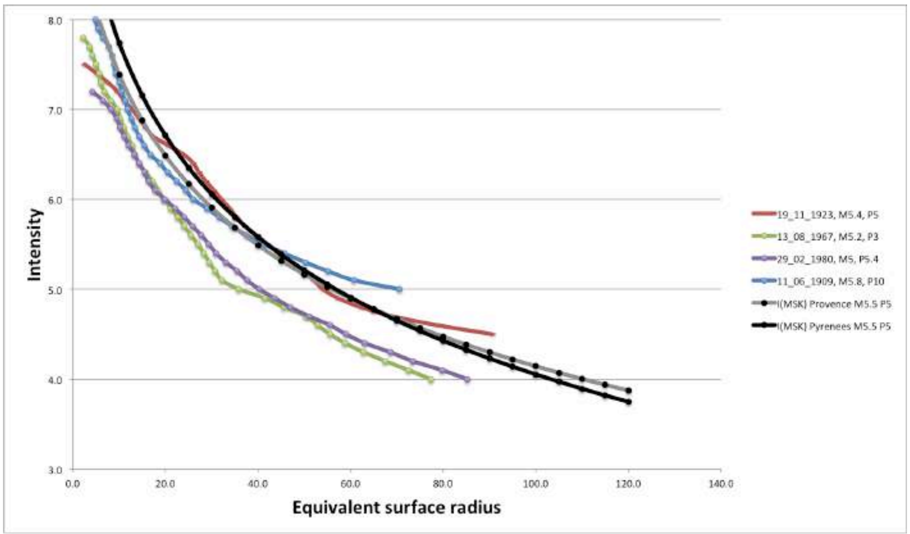


Figure 34: comparison of Bakun and Scotti 2006 attenuation relation and Equivalent surface radius for Provence and Pyrenees.

For the Provence-Pyrenees region, the Bakun and Scotti attenuation relation fits well with the short distance slope for depth of 5km and magnitude 5.5. The global shape of the relation follows the observations. For 1909 and 1923, at large distance the curves seem to move out from the other observations and Bakun and Scotti attenuation laws. It could be related to a lack of data and then overestimation of isoseismals area.

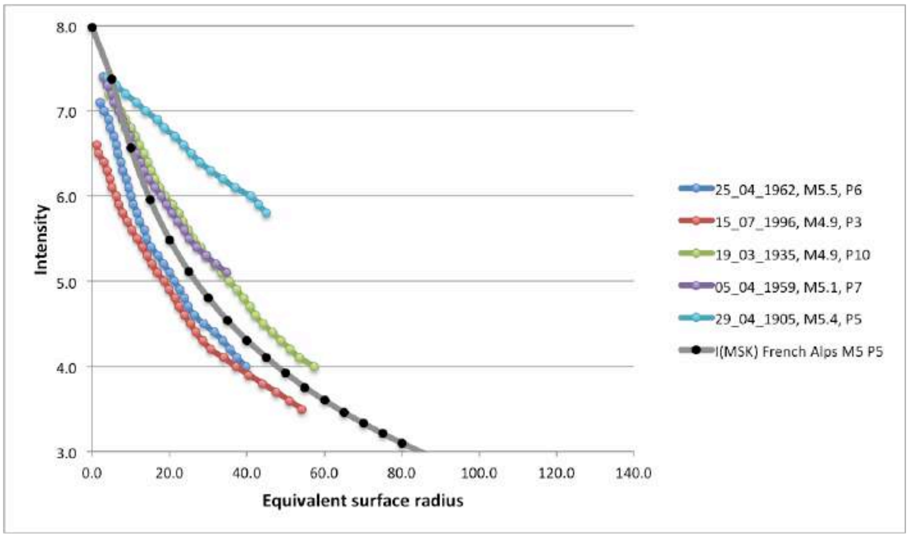


Figure 35: comparison of Bakun and Scotti 2006 attenuation relation and Equivalent surface radius for French Alps.

For the French Alps, the Bakun and Scotti attenuation relation shape fits well with the observations for depth of 5km and magnitude 5. It is nevertheless a bit higher in the magnitude level.

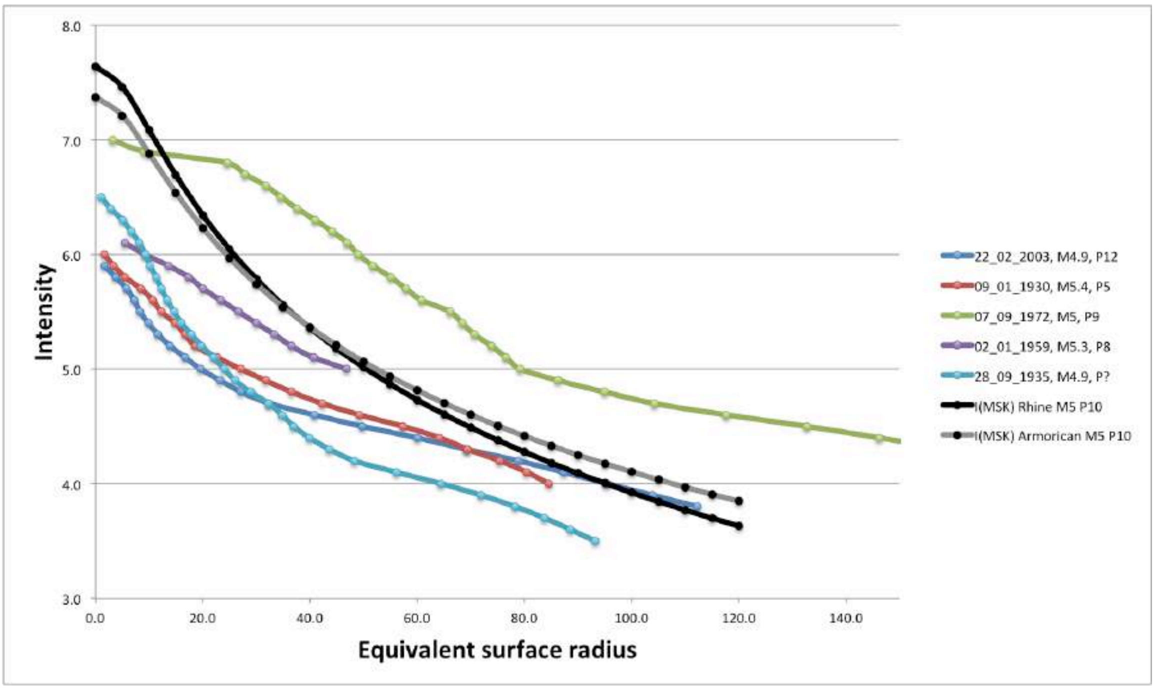


Figure 36: comparison of Bakun and Scotti 2006 attenuation relation and Equivalent surface radius for Rhine and Armorica regions.

For the Armorica and Rhine region, the Bakun and Scotti attenuation relation shape does not fit well with the observations (curves obtained from our procedure) for depth of 10km and magnitude 5. The level at short distance is much higher than the observations despite the slope is similar that seems to be induced by an overestimation at the epicentre zone, of about one intensity degree for the 2003 event (max intensity = VI-VII). At long distance, the level and the slope converge with the 2003 event for the Rhine relation and with the 1930 for the Armorica relation giving then a better estimation.

Discussion and limitation

Discussion and Perspectives:

In this part, we will discuss the potential impact on the estimation of the Magnitude and depth of our procedure, from IDP to the interpretation and give some perspectives.

The Intensity Data Points (IDP)

MSK or EMS98:

The IDPs are considered as truth-values. The data could be in MSK or EMS98 scale. This two scales should not change the results but the strong advantage of the EMS98 is to better take into account the vulnerability and the statistic of the damage to get a more robust "ground shaking strength assessment" or Intensity value. The potential bias in MSK is to overestimate intensity, which could be based on only few observations representing the highest impact on buildings. The impact on intensity assessment would start from Intensity V to VI. This point was not taken into account in our study.

The datasets density is related first to the density of cities in the affected area. It is the maximum possible density of IDPs. Notice that the cities repartition is not regular inducing anyway variable density IDPs. In fact, we do not have IDPs for all the cities except for the most recent event where we have all cities (BCSF survey) including far distance IDP through internet individual forms (www.franceseisme.fr - BCSF website), medium to short distance IDP through collective forms (authorities enquiry by BCSF) and field investigations in the damaged cities by the G.I.M. (Groupe d'intervention macrosismique coordinated by the BCSF).

Incomplete IDP in the region affected by the earthquake.

Reduced IDP coverage: In modern time, this is due to city authorities refusing to fill the form. It concerns today only few cities with mostly low Intensity. When we move to the past, even in XXth century, the IDP coverage is variable and some region show clearly incomplete datasets. If this is due to the lost of the lower Intensities value in the area, it will induce, whatever is the method used, an overestimation of intensity at a certain distance in comparison to a full dataset. For example it will increase the isoseismal surface made by numerical methods (as kriging) or by expert interpretation. This impact must be taken into account for historical event analysis when compared to recent events. When the observed attenuation is much lower than the usually observed in the region, it is important to check that point.

No IDP at all in some region:

- When this happens for modern period, it is due to authorities refusing to fill the form (as the Marne department after the Rambervillers 2003 event). This could have a very important impact as some department could be without any Intensity producing incomplete maps comparable to the Lambesc (1909) earthquake for the Var region.

- When the event is near sea shoreline, the case for all Western France and South-Eastern France, the IDP coverage is abruptly cut. We can also find this situation along the other border of

France when no foreign data are available. This could be solved by combining transfrontiers data as made for Rambervillers earthquake (Cara et al. 2005, Cara et al. 2007).

To avoid any impact of such situation, we used only complete isoseismal in our analysis and interpretation. Also we limited the distance from the last IDP to calculate new Intensity value to avoid inconsistent results. Another way, when the coverage is 180 degree or more, is to consider hypothetical symmetry in the isoseismal and correct the isoseismal area in proportion. In our study, we used it only for the 1972 Oléron earthquake that is in an optimal situation, which allows us to multiply by 2 the overall surface. Nevertheless, this correction could introduce some bias. The possible improvement should be considered before applying such method.

The kriging:

The main advantage of the kriging is that it smooths the local heterogeneities as site effects. The obtained isoseismals surfaces are then more representative of the source characteristics and regional attenuation. Any other method that stay at observed data (Voronoy, IDW etc) will be impacted by such heterogeneities that disturb the results, as the source parameters (Mw and depth) are not the origin of such heterogeneities.

The kriging is the method we selected to solve at best our challenge. Nevertheless, we have to keep in mind that the highest intensities (as in epicentre area) are not modelled by this method as they are surrounded by many lower intensities inducing a reduction of these highest intensities by kriging. The solution would be to apply adapted kriging parameters in the epicentre area but this could induce a jump between results.

The epicentral area IDP. We observe in many earthquakes that the highest Intensities are not at epicentre. The reason is that there is no observation at the epicentre in most cases and that the highest values are often at more than 10 km (see Barcelonnette earthquake of 2014-04-07). Also, the highest intensities are often the places of site effects. That is the case for the Barcelonnette earthquake for which the macroseismic epicentre would be shifted of about 10 km from its real place. Nevertheless, the underestimated epicentre area intensity is not an important problem for our purpose.

Global and local kriging. The global kriging should not be applied as the calculated point, at far distance from observations, gives very inconsistent results. The use of local kriging improves our results by limiting them to well constrained areas. The disadvantage is that some areas with observed IDP are not modelled due to too limited number of data. The adjusted parameters, as the maximum distance calculation, could be adapted (longer distance) to the datasets keeping in mind that the quality of the result would decrease.

Isoseismals Surfaces:

The surfaces are calculated without expert input except for the variogram model that is strategic for the kriging interpolation. Converted in equivalent surface circle radius, we delete any impact of the irregular geometry of the isoseismals. This radius can be considered as the impact of the source parameter and the regional attenuation. The result is a curve “unique” (radius versus intensity) deleting all the effect of the variability of intensity at a certain distance as in the usual IDP methods. This brings us to a very comfortable situation allowing us to compare event between them.

Master events and available reference Mw and depth data.

The difficulty for Intensity / Mw-Depth is to use well-constrained Mw-Depth parameters. Our work has been waiting the last Mw-Depth parameter before comparing the events (Denieul 2014, SI-Hex 2014, Benjumea et al. october 2014). The last updates have been done beginning of 2014 October using last results of Benjumea et al.. Nevertheless, we have to keep in mind that the depth is poorly constrained except for few events (see table 4) as well as the magnitude due to limited historical seismogram as for the 1938 Flandres event when Benjumea proposed first a Mw of 4.8 upgraded to 5.1 (difficulty due to low azimuthal coverage of the seismogram). Therefore, we considered all the results (Denieul 2014, SI-Hex 2014, Benjumea et al. 2014) but we used as "master events" (see table 4) the event the most constrained to estimate difference in Mw and depth. The solution is anyway relative to instrumental observations on which we have to refer. We did not produce new attenuation relations as we consider our dataset too limited. The application of our procedure to various recent events, analysed precisely by BCSF since 2000, is still necessary.

Comparison with published attenuation relations.

We compared Levret et al 1994 and Bakun & Scotti 2006. We selected Bakun & Scotti 2006 as they include regional attenuation relation, differences that were obvious from our results (surface versus intensity). The fit of the proposed relation and our data is very good except for the Rhine and Armorica region where the difference is very important for distances less than 60 km. Therefore, using our procedure for radius calculation, it is possible to keep the Bakun and Scotti 2006 relations for Alps, Provence and Pyrenees. This confirms the consistency of our procedure, the good estimation of isoseismal surface radius, and its proxy as Mw and depth parameter.

The Rhine and Armorica relation should not be used or used with caution. We prefer to use “master event” method until a more adapted relation is published.

Other possible method to estimate Mw and depth with IDP:

Our aim was not to compare our procedure with other based on IDP but to test and validate a procedure based on automatic isoseismals assessment (with no expert influences) and relation between isoseismal surface and Mw-depth with the most updated estimations in the frame of the WP1 SIGMA project. The estimation of such parameter is a challenge, even for instrumental time as we could observe during the SI-Hex Project (Cara et al. 2014; M. Cara, Y Cansi, A. Schlupp and al. 2015). If the method presented here gives very good results and could be applied alone, it is always necessary to confront the results of various methods when approaching the estimation of Mw and Depth using IDP, especially for historical time.

Conclusions

The purpose of this work was to test the possibility to use isoseismals area, deduced from observed IDP and a numerical approach to avoid “expert interpretation impact”, to characterise Moment magnitude and depth parameters for earthquakes of the XXth century. The work has been based on precise instrumental parameters produced by recent work as the SI-Hex 2014 project (CNRS, Universities and MEDDE), Denieul et al. 2014 (WP1 Sigma) and Benjumea et al. 2014 (WP1 Sigma) study.

The local kriging procedure with the adjusted parameter that we defined allows estimating, using master event, Mw and Depth parameter from IDP. The kriging procedure and calculation of isoseismal area has been nearly automatized, avoiding expert interpretation impact that could introduce differences in the event analysis. The analysis of 22 events shows various situations and limitations for such analysis. It shows also the advantage of data processed through a unique numerical method well calibrated that allow a better comparison with “master events”.

The plot of “radius” versus intensity appears to be a very good proxy to estimate Mw and Depth by using “master events” that are precisely known. The obtained curves are fitting well with the Bakun and Scotti 2006 attenuation relations except for Rhine and Armorica area where their relation does not fit the data.

With our method, we pointed out some events for which the instrumental values are not fitting the observations and we proposed alternative “estimations”. Notice that the last work based on instrumental data (Manchuel et al. 2015) always reduce the difference with our results, confirming our results, and more important, our approach.

More events have to be analysed to produce constrained relations between our procedure and associated curves and Mw and depth parameters, particularly in the area of Armorica and Rhine.

Annexe

Annexe1: Deterministic interpolators

Inverse Distance Weighted (IDW)

Inverse Distance Weighted (IDW) interpolation implements a basic law of geography, things that are close to one another are more alike than things that are far apart.

To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. Those measured values closest to the prediction location have more influence on the predicted value than those that are farther away (hence the name “inverse distance weighted”). We can determined which values are included in the calculation by specifying and customizing the search neighbourhood, which is the region of the map around a selected point, in which data points are considered for the extrapolation.
IDW assumes that each measured point has some local influence that diminishes with distance. In the figure 1 you can see three different curves that show how fast the influence of a point decays with distance from the prediction location. For the blue curve, all locations (observed data) get the same weight, regardless of how far they are from the prediction location. In the green curve, there is a mild decrease in a point’s influence as it gets farther from the prediction location. In the red curve, there is the most dramatic decrease in a point’s influence as it gets farther from the prediction location.

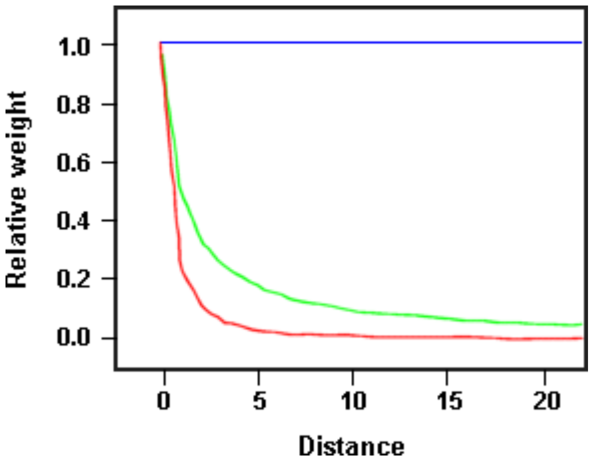


Figure 1 In IDW, the predictive influence (weight) of a measured value depends on its distance from the prediction location. The strength of the dependency can be adjusted.

Notice that as the distance approaches zero, the relative weight approaches one. This means that if one measured point is very close to the prediction location, it will receive almost all of the weight. Thus, IDW is an "exact" interpolator, meaning that the predictions will be exactly equal to the data value when predictions occur at locations where data have already been collected.

Global polynomial

Global polynomial interpolation fits a smooth surface to the sampled data points. In contrast to IDW, it does not use local information. Global polynomial interpolation fits a polynomial regression to the x- and y-coordinates.
Suppose that the elevation data have been collected as in the figure 2. The black points are measured elevation values.

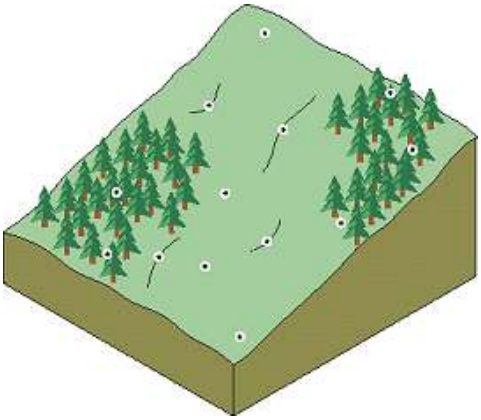


Figure 2: Measured altitude points on the field, black dots, to produce a DEM.

- A *first-order polynomial* fits a rigid plane to the data. Visualize fitting a flat sheet of paper to the elevation points (figure 3). Of course, the elevation values will include lots of little dips and bumps besides the general trend seen in the figure above. The flat surface of a global polynomial will smooth out all of the little bumps. Because the surface is rigid, it will not pass exactly through the sampled data points. This means that the global polynomial is not an exact interpolator; rather, it smoothes over fine-scale details.

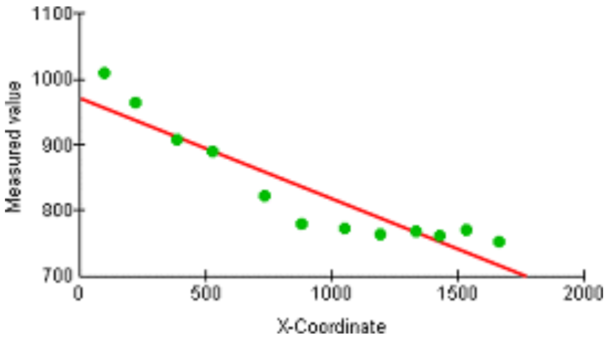


Figure 3: A first order global polynomial surface in cross-section. The surface (red line) captures coarse-scale pattern in the data. It does not pass through the sampled data (green points).

- A flat piece of paper will not represent a landscape with a valley. In that case, you can choose a *second-order polynomial* that lets you "bend" the piece of paper once in one direction (figure 4).

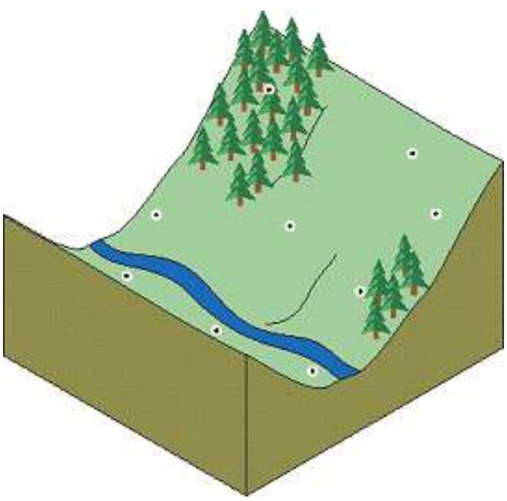


Figure 4: A second-order polynomial allows a single bend in the surface.

Likewise, a third-order polynomial allows two bends and so forth. You can choose up to a tenth-order polynomial in the Geostatistical Analyst. Global Polynomial interpolation is the only method in Geostatistical

Analyst that does not use a search neighborhood. If you add the idea of a search neighbourhood to Global Polynomial interpolation, you get Local Polynomial interpolation.

Local polynomial

As described before, global polynomial interpolation creates a surface from a single polynomial formula. Local polynomial interpolation creates a surface from many different formulas; each of them is optimized for a neighborhood.

The neighbourhood shape, maximum and minimum number of points, and sector configuration can be specified. In addition, as with IDW, the sample points in a neighbourhood can be weighted by their distance from the prediction location. Thus, local polynomial interpolation produces surfaces that better account for local variation.

A first-order local polynomial fits a single plane through the data points in the search neighborhood, but keeps only the fitted value at the prediction location. The neighbourhood then slides over to the next prediction location (each neighbourhood thus largely overlaps the ones around it) and the process is repeated. In each case, only the value at the prediction location is kept.

A second-order local polynomial fits a surface with a bend in it to each search neighborhood, a third-order local polynomial fits a surface with two bends to each neighborhood, and so on. Local polynomials are more flexible than global ones. For example, consider the case of a landscape that slopes, levels out, and then slopes again.

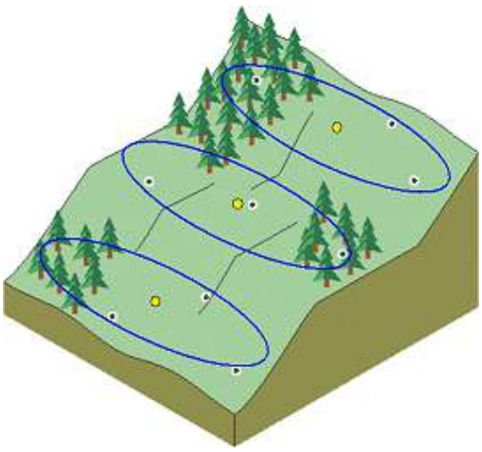


Figure 5: A different plane is fitted to each of the neighbourhoods (blue outlines) that are centred on the prediction locations (yellow points).

A single global polynomial will not fit this landscape very well. Local polynomial interpolation, however, can fit a different plane to each neighbourhood centred on a prediction location. As the interpolator considers each location in turn, the neighbourhoods overlap. The value used for each prediction is that of the fitted polynomial at the centre of the search neighbourhood.

Although it is more flexible than global polynomial interpolation, local polynomial interpolation is not an exact interpolator like IDW.

Radial basis functions

You can think of the surface created by radial basis functions as a rubber membrane that is fitted to each of the measured data points while minimizing the total curvature of the surface. Because the surface must pass through each sampled point, radial basis functions are exact interpolators. Geostatistical Analyst uses five radial basis functions. They are similar, but create slightly different surfaces because they use different math to fit the surface to the sample points.

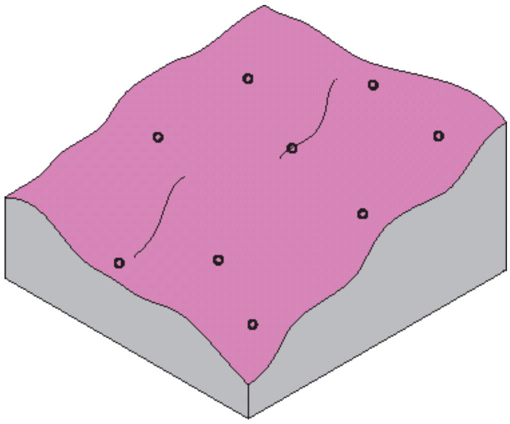


Figure 6: Interpolation using radial basis functions is shown by the purple surface; think of it as a fairly stiff rubber sheet that bends and folds to fit exactly to the sample data points.

Annexe 2: Interpolator based on probability model:

The second family of methods of interpolation includes geostatistics techniques (such as the method of kriging), which are based on statistical models including the autocorrelation, that is the statistical relations between the measured points. Consequently, geostatistics techniques have not only the capacity to produce a surface of prediction, but they can also supply measures as for the certainty or the accuracy of these predictions.

The Kriging

The kriging approach:

Kriging wears the name of his precursor, the South African mining engineer D.G. Krige (1951). In the 50s, Krige developed a series of empirical statistical methods to determine the spatial distribution of ores from a set of drillings. It is however French Matheron (1963 and 1972), which formalized the approach by using the correlations between the drillings to consider its spatial distribution. He baptized the method " Kriging ". He was also the first one has to use the term "geostatistics" to indicate the statistical modelling of spatial data. The same ideas were developed, at the same time, in the USSR by L.S. Dandy. Dandy baptized his method "optimal interpolation". He introduced the notion of "objective analysis" to describe this approach based on the correlations. It is the name under which the method is known in meteorology.
In oceanology, Bretherton and al (1976) introduced the method. It is known under the name of "method of interpolation of Gauss-Markov", according to the name that we give him formally in the books of statistics (see Liebelt 1967, for example).

Kriging presents a different way to think about prediction than do the deterministic interpolators. In Kriging, a predicted value depends on two factors: a trend and an additional element of variability. This is an intuitive idea with plenty of analogies in the real world. For instance, if you go from the ocean to the top of a mountain, you have an upward trend in elevation. However, there is likely to be variation on the way—you will go both up and down when crossing valleys, streams, knobs and other features.
In Kriging, the trend part of a prediction is called “the trend”. The fluctuation part is called “spatially-autocorrelated random error”. "Error" doesn't mean a mistake; it just means a fluctuation from the trend. "Random" means that the fluctuation (error) away from the trend is not known in advance, it could be up or down in elevation, it could be above or below the average climb of the stock market. "Spatially-autocorrelated" means that, while the fluctuations are not known exactly in advance, they have tendencies to be above the average or below the average together whenever they are in close proximity. This is positive spatial autocorrelation. It is also possible to have negative spatial correlation, where if one site is above the average, a nearby site tends to be below the average. Two assumptions are made about the spatially-autocorrelated random error. The first assumption is that it is 0 on average. In other words, some fluctuations will be on one side of the trend and some will be on the other side, but the differences, on average, will cancel each other out. The second assumption is that the autocorrelation of the error is purely spatial; it depends only on distance and not on any other property (such as position) of a location. This assumption is technically known as "stationarity."

Ordinary Kriging is done when one assumes there is no trend in the data, or, if there is one, it is weak enough that you can ignore it. Assuming that there is no trend in the data is mathematically equivalent to assuming that the data have a constant mean value. The points that make up the interpolated surface are the mean of all points in the search neighbourhoods.

Universal Kriging assumes there is a trend in the data, but the terms of the trend function are not known in advance. The data values are thought of as random errors that fluctuate around the unknown trend. The random errors are autocorrelated, meaning they tend to be above or below the trend in a way similar to their neighbours. The points that make up the interpolated surface are the mean of all points in the search neighbourhoods, plus the trend.

Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. The Kriging tool fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. Kriging is a multistep process; it includes exploratory statistical analysis of the data, variogram modeling, creating the surface, and (optionally) exploring a variance surface. Kriging is most appropriate when you know there is a spatially correlated distance or directional bias in the data. It is often used in soil science and geology.

Kriging is similar to IDW in that it weights the surrounding measured values to derive a prediction for an unmeasured location. The general formula for both interpolators is formed as a weighted sum of the data:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

where:

$Z(s_i)$ = the measured value at the *i*th location

λ_i = an unknown weight for the measured value at the *i*th location

s_0 = the prediction location

N = the number of measured values

In IDW, the weight, λ_i, depends solely on the distance to the prediction location. However, with the kriging method, the weights are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points. To use the spatial arrangement in the weights, the spatial autocorrelation must be quantified. Thus, in ordinary kriging, the weight, λ_i, depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location. The following sections discuss how the general kriging formula is used to create a map of the prediction surface and a map of the accuracy of the predictions.

The variogram:

The spatial interpolation is a classic problem of estimation of a function F (x), where X = (x, y), in a point Xp of the plan from known values of F in a certain number, m, of surrounding points Xi:

$$F(x_p) = \sum_{i=1}^{m} W_i \cdot F(x_i) \quad (1)$$

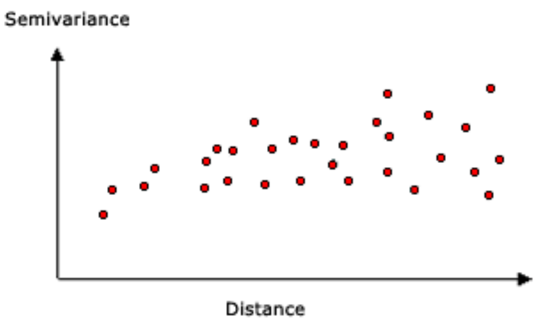
The problem consists in determining the weighting, i.e. Wi, of each of the surrounding points. There are several manners to choose these weights. The two main known methods are the linear interpolation (according to the inverse of the distance IDW) and the method of the cubic splines (adjustment of cubic polynomials). Kriging chooses rather the weights from the degree of similarity between the values of F, i.e. from the covariance between points according to the distance between these points.

To make a prediction with the kriging interpolation method, two tasks are necessary:
- Uncover the dependency rules.
- Make the predictions.

To realize these two tasks, kriging goes through a two-step process:
- It creates the variograms and covariance functions to estimate the statistical dependence (called spatial autocorrelation) values that depend on the model of autocorrelation (fitting a model).
- It predicts the unknown values (making a prediction).

It is because of these two distinct tasks that it has been said that kriging uses the data twice: the first time to estimate the spatial autocorrelation of the data and the second to make the predictions.

Often, each pair of locations has a unique distance, and there are often many pairs of points. To plot all pairs quickly becomes unmanageable. Instead of plotting each pair, the pairs are grouped into lag bins. For example, compute the average semivariance for all pairs of points that are greater than 40 meters apart but less than 50 meters. The empirical semivariogram is a graph of the averaged semivariogram values on the y-axis and the distance (or lag) on the x-axis (see diagram below).



Example of diagram of empirical semivariogram

Spatial autocorrelation quantifies a basic principle of geography: things that are closer are more alike than things farther apart. Thus, pairs of locations that are closer (far left on the x-axis of the semivariogram cloud) should have more similar values (low on the y-axis of the semivariogram cloud). As pairs of locations become farther apart (moving to the right on the x-axis of the semivariogram cloud), they should become more dissimilar and have a higher squared difference (moving up on the y-axis of the semivariogram cloud).

Understanding a semivariogram—Range, sill, and nugget

As previously discussed, the semivariogram depicts the spatial autocorrelation of the measured sample points. Because of a basic principle of geography (things that are closer are more alike), measured points that are close will generally have a smaller difference squared than those farther apart. Once each pair of locations is plotted after being binned, a model is fit through them. Range, sill, and nugget are commonly used to describe these models.

Range and sill

When you look at the model of a semivariogram, you will notice that at a certain distance the model levels out. The distance where the model first flattens is known as the range. Sample locations separated by distances closer than the range are spatially autocorrelated, whereas locations farther apart than the range are not.

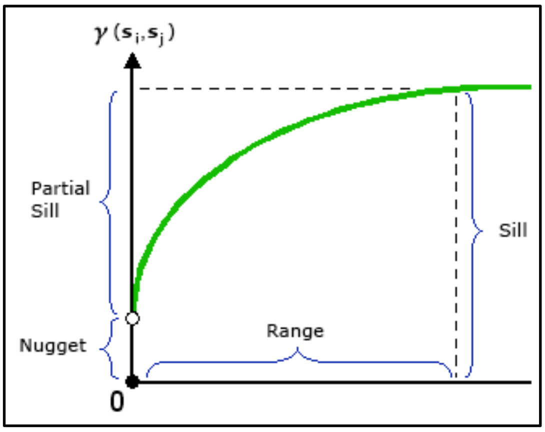


Figure 7: Illustration of Range, Sill, and Nugget components

The value at which the semivariogram model attains the range (the value on the y-axis) is called the sill. A partial sill is the sill minus the nugget. The nugget is described in the following section.

Nugget

Theoretically, at zero separation distance (for example, lag = 0), the semivariogram value is 0. However, at an infinitely small separation distance, the semivariogram often exhibits a nugget effect, which is a value greater than 0. If the semivariogram model intercepts the y-axis at 2, then the nugget is 2.

The nugget effect can be attributed to measurement errors or spatial sources of variation at distances smaller than the sampling interval (or both). Measurement error occurs because of the error inherent in measuring devices. Natural phenomena can vary spatially over a range of scales. Variation at microscales smaller than the sampling distances will appear as part of the nugget effect. Before collecting data, it is important to gain an understanding of the scales of spatial variation in which you are interested.

Like IDW interpolation, kriging forms weights from surrounding measured values to predict unmeasured locations. As with IDW interpolation, the measured values closest to the unmeasured locations have the most influence. However, the kriging weights for the surrounding measured points are more sophisticated than those of IDW. IDW uses a simple algorithm based on distance, but kriging weights come from a semivariogram that was developed by looking at the spatial nature of the data. To create a continuous surface of the phenomenon, predictions are made for each location, or cell centers, in the study area based on the semivariogram and the spatial arrangement of measured values that are nearby.

Annexe 3: Atlas of earthquakes analysed by kriging interpolation

Event name	Mw	Mw author	depth	depth author	Year-month-day	epic. Int. MSK	IDP numbers
Chamonix - Mont-Blanc	5.4	Benjumea oct2014	5	Benjumea oct2014	1905-4-29	7.5	302
Lambesc	5.8	Benjumea oct2014	10	Benjumea oct2014	1909-6-11	8.5	475
Jura Souabe	5.5	Benjumea oct2014	4	Benjumea oct2014	1911-11-16	8.5	480
Val d'Aran	5.4	Benjumea oct2014	5	Benjumea oct2014	1923-11-19	8	652
Kayserstuhl	5	Kunze 1986	15	Karnik 1969	1926-6-28	7	735
Landes de Lanvaux	5.4	Benjumea oct2014	5	Benjumea oct2014	1930-1-9	7	543
Embrunais	4.9	Benjumea oct2014	10	Benjumea oct2014	1935-3-19	7	254
Angoumois	4.9	EMEC 2012			1935-9-28	7	647
Offenburg	4.6	EMEC 2012	30	Karnik 1969	1935-12-30	7	834
Flandres (Belgique)	5.1	Benjumea oct2014	30	Benjumea oct2014	1938-6-11	7	1445
Valais (Suisse)	5.8	Benjumea oct2014	5	Benjumea oct2014	1946-1-25	7.5	476
Valais	5.5	Fritsche et al. 2012			1946-5-30	7	388
Cornouaille	5.3	Benjumea oct2014	5	Benjumea oct2014	1959-1-2	7	784
Ubaye	5.1	Benjumea oct2014	10	Benjumea oct2014	1959-4-5	7.5	207
Vercors	5.5	SI-Hex2014	6	Benjumea oct2014	1962-4-25	7.5	506
Mer Ligure-Imperia	6.1	Benjumea oct2014	6	Benjumea oct2014	1963-7-19	7	410
Arette	5.2	SI-Hex2014 coda	3	Benjumea oct2014	1967-8-13	8	839
Oléron	5	SI-Hex2014 coda	11	SI-Hex2014 LDG	1972-9-7	7	446
Piemont (Italie)	4.5	SI-Hex2014	10	SI-Hex2014 LDG	1980-1-5	7	491
Ossau	5	SI-Hex2014 coda	5.4	SI-Hex2014 OMP	1980-2-29	7.5	1323
Annecy	4.9	SI-Hex2014 coda	3	SI-Hex2014 GRN	1996-7-15	7	782
Rambervillers	4.9	SI-Hex2014 coda	12	LDG	2003-2-22	6.5	5212

The following atlas (88 maps) represents the results of the Kriging methods applied to 22 events selected in the XXth century. They are classified by date.

For each of them, the title gives the date of the event, the common name associate, Mw, Depth and minimum Intensity isoseismal constrained by the kriging results.

4 maps follow it:
The first map shows the IDP (Intensity III and more)
The second map shows the interpolation by kriging (Intensity III and more)
The third map shows the IDP overlying the kriging interpolation (Intensity III and more)
The fourth map shows the kriging interpolation and the isoseismals (Intensity III and more)

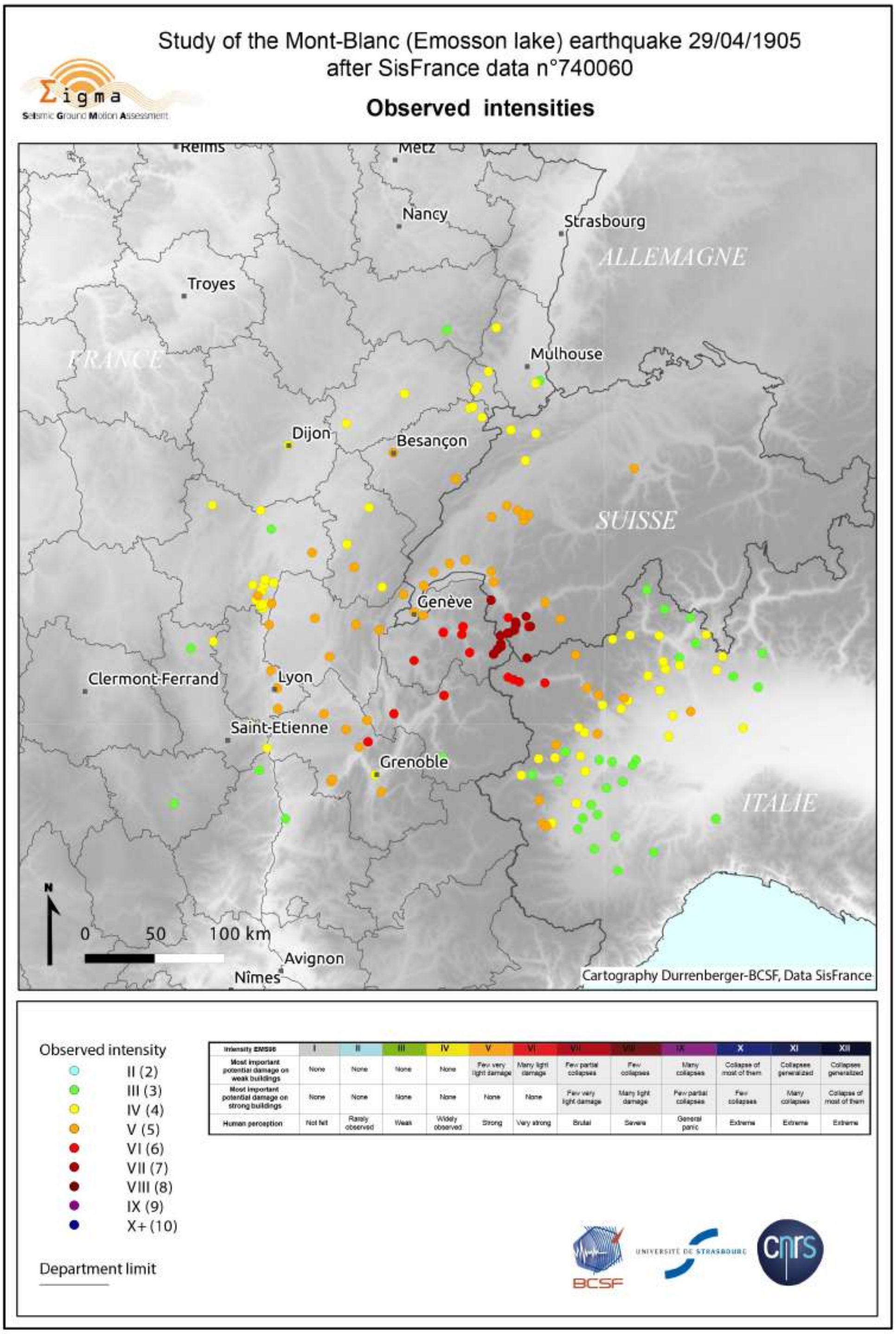
When the name is followed by "(Auto)", it does mean that the event has been processed with the automatic procedure, the only user interaction being the selection of the model fitting the variogram. The ground resolution used for the kriging is 0.4km for the "auto" process. They include the intensity II and more. The calculation includes the intensity I

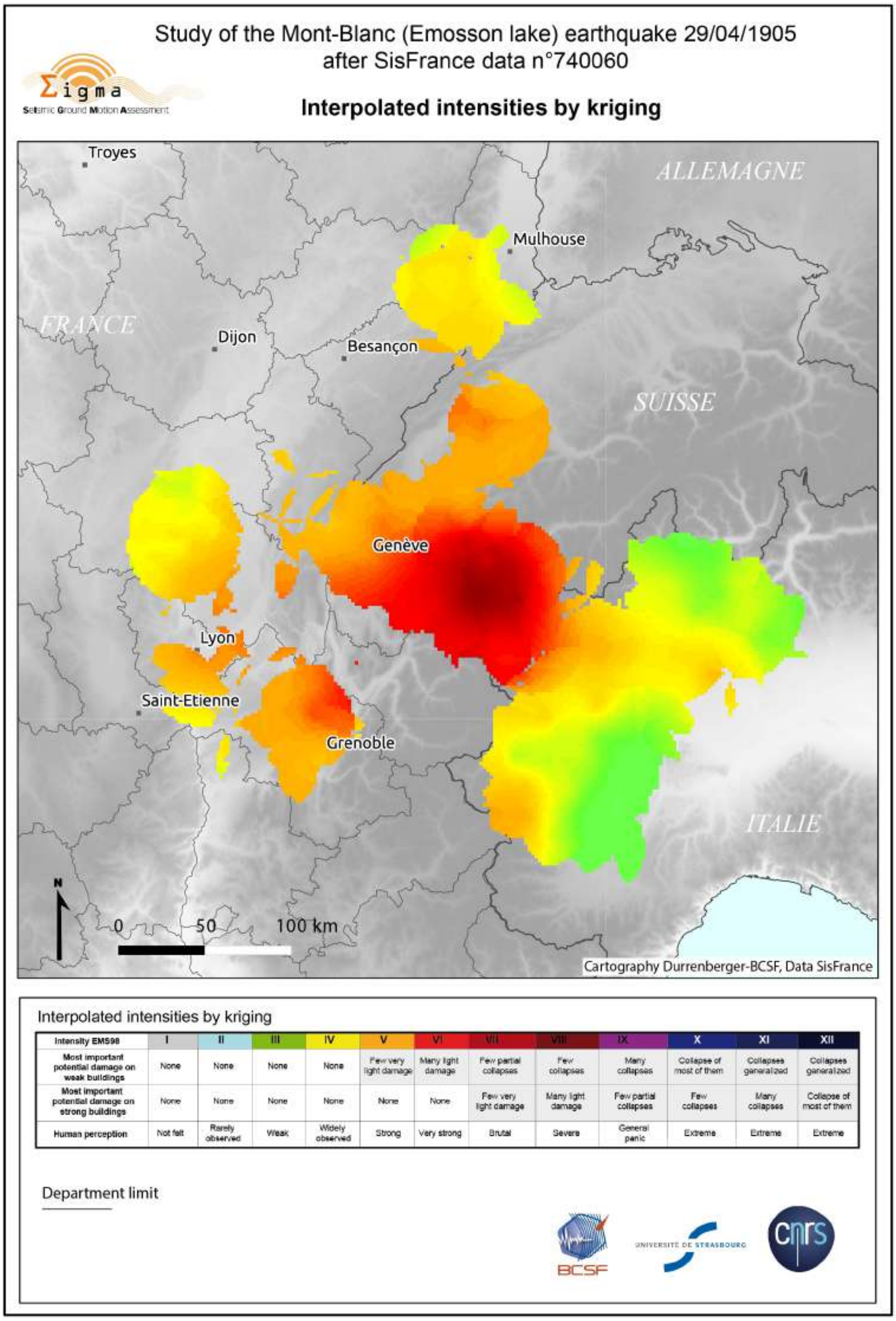
For the others maps, the data has been calculated with a manual application of the procedure and a ground resolution of 2km. They include the intensity III and more and the calculation does not include intensities I and II.

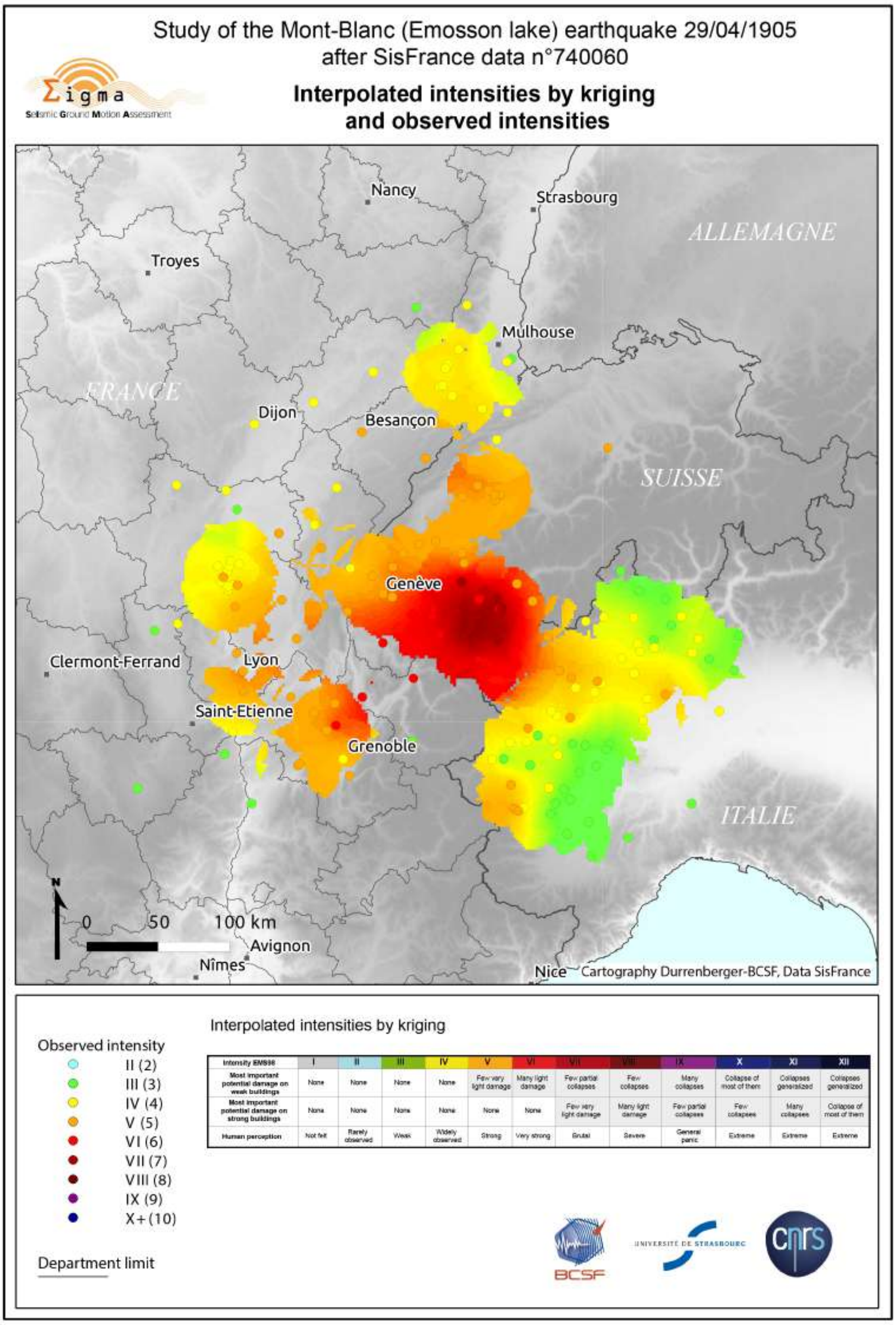
The map design has been made using QGis and for the event labelled "(Auto)" using ArcGis softwares.

The data are overlaid on the topography in grey scale that has been shaded for the event labelled "(Auto)".

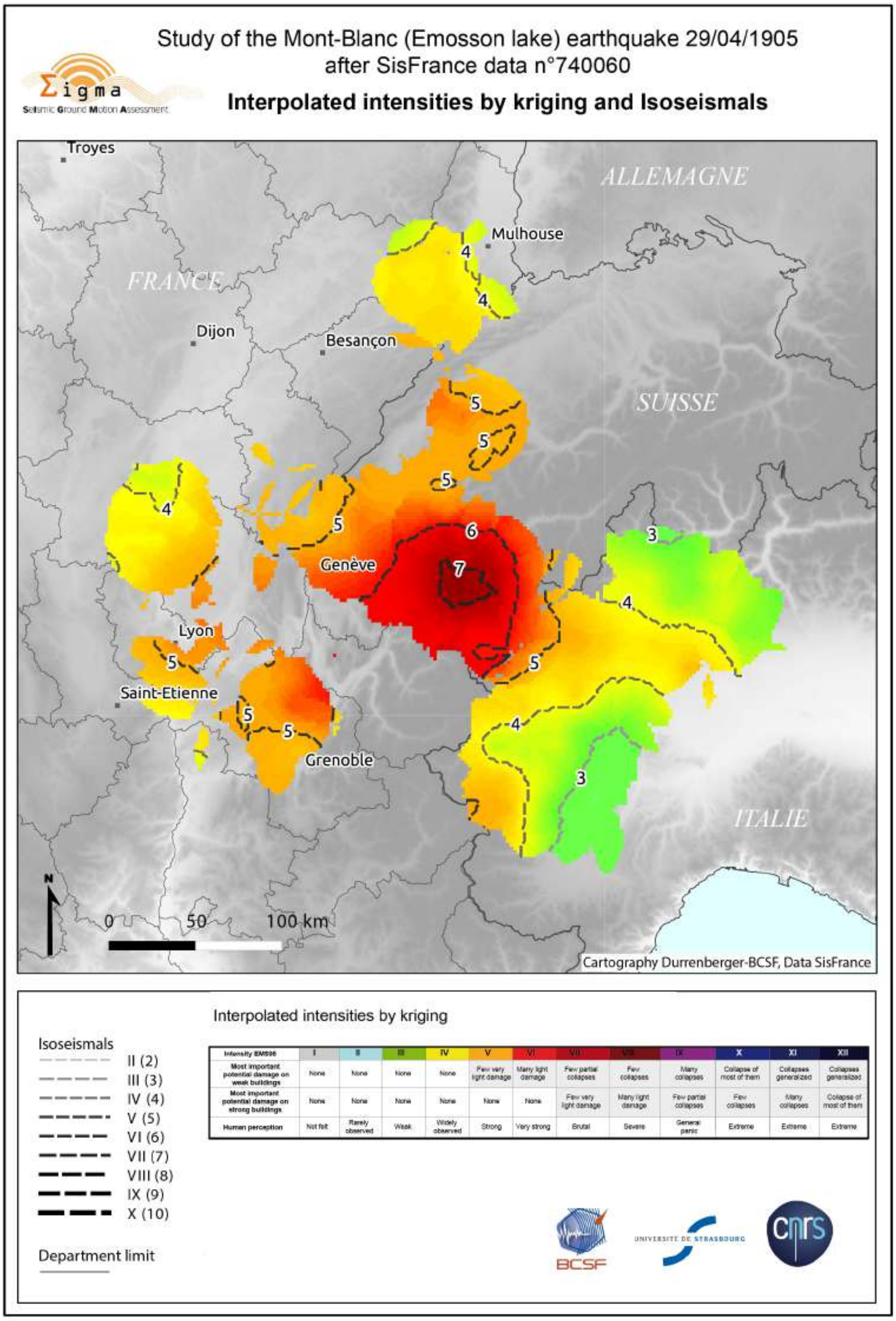
1905-04-29: Mont Blanc earthquake, Mw=5.4, Depth=5km, Isoseismal-min (Kriging)=5.8




Study of the Mont-Blanc (Emosson lake) earthquake 29/04/1905
after SisFrance data n°740060
Interpolated intensities by kriging
Troyes
ALLEMAGNE
Mulhouse
FRANCE
Dijon
Besançon
SUISSE
Genève
Lyon
Saint-Etienne
Grenoble
ITALIE
N
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Interpolated intensities by kriging
Intensity EMS98: I, II, III, IV, V, VI, VII, VIII, IX, X, XI, XII
Most important potential damage on weak buildings: None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them, Collapses generalized, Collapses generalized
Most important potential damage on strong buildings: None, None, None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them
Human perception: Not felt, Rarely observed, Weak, Widely observed, Strong, Very strong, Brutal, Severe, General panic, Extreme, Extreme, Extreme
Department limit
BCSF
UNIVERSITÉ DE STRASBOURG

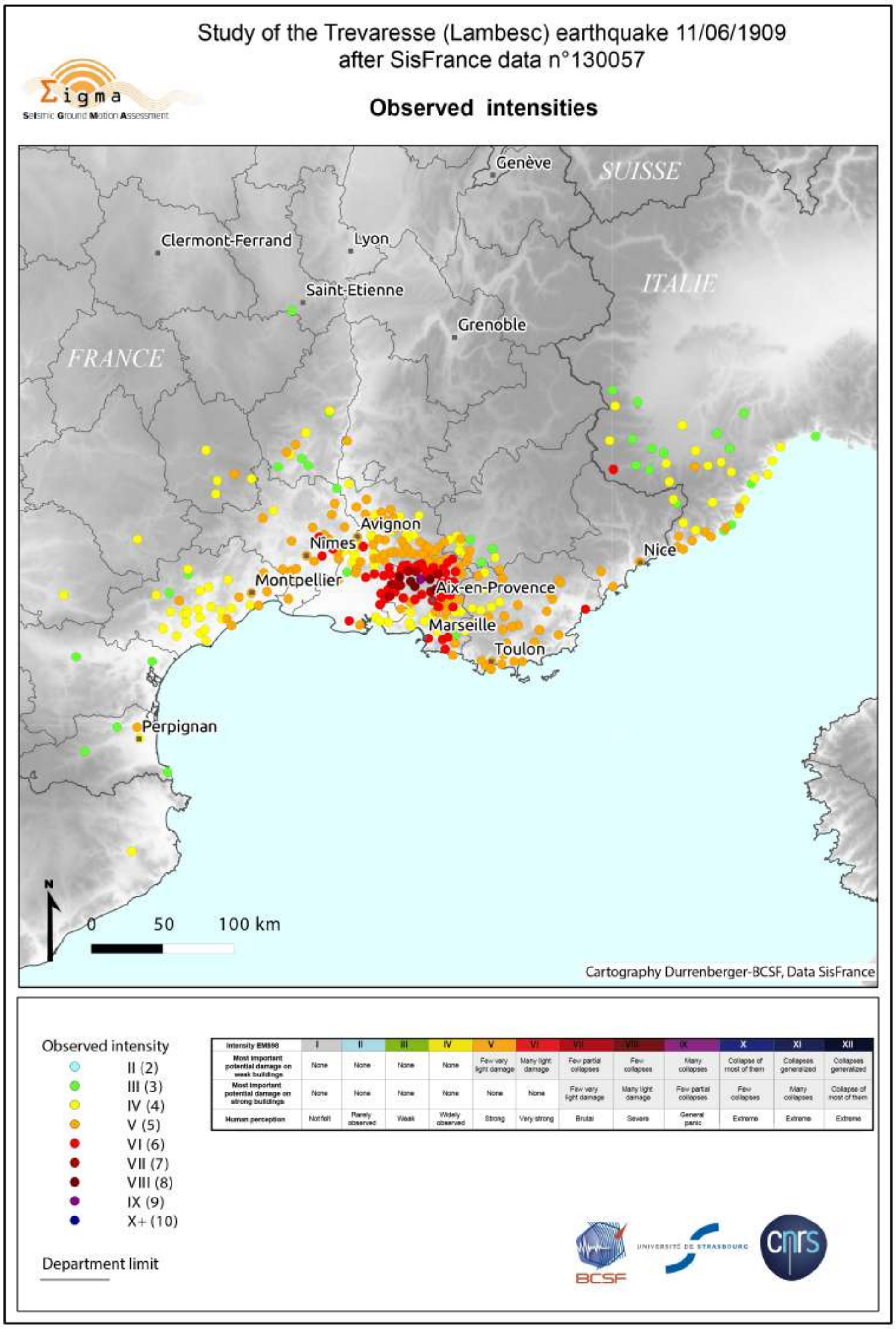


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Study of the Mont-Blanc (Emosson lake) earthquake 29/04/1905
after SisFrance data n°740060
Interpolated intensities by kriging and Isoseismals
Troyes
ALLEMAGNE
Mulhouse
FRANCE
Dijon
Besançon
SUISSE
Genève
Lyon
Saint-Etienne
Grenoble
ITALIE
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Isoseismals
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98
I
IV
V
VI
X
XI
XII
Most important potential damage on weak buildings: None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them, Collapses generalized, Collapses generalized
Most important potential damage on strong buildings: None, None, None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them
Human perception: Not felt, Rarely observed, Weak, Widely observed, Strong, Very strong, Brutal, Severe, General panic, Extreme, Extreme, Extreme
BCSF
UNIVERSITE DE STRASBOURG

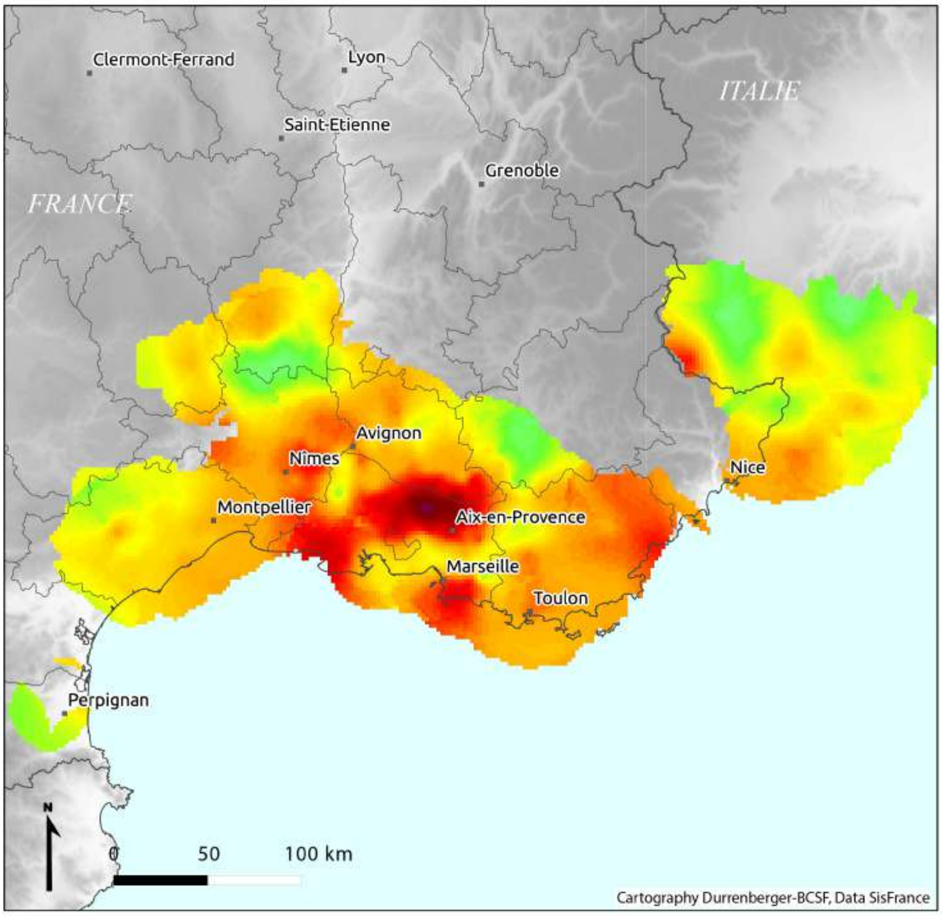
1909-06-11: Lambesc earthquake, Mw=5.8, Depth=10km, Isoseismal-min (Kriging)=5.0



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of the Trevaresse (Lambesc) earthquake 11/06/1909
after SisFrance data n°130057

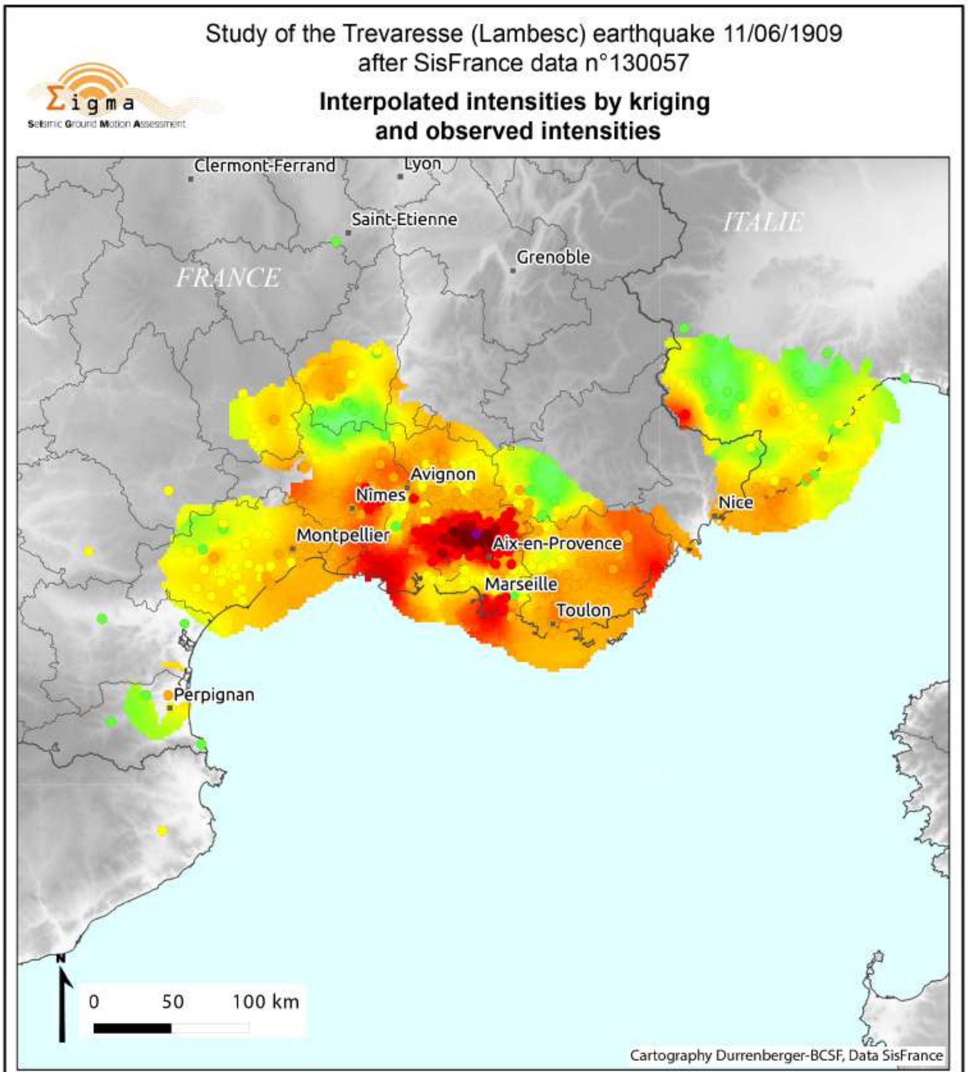
Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

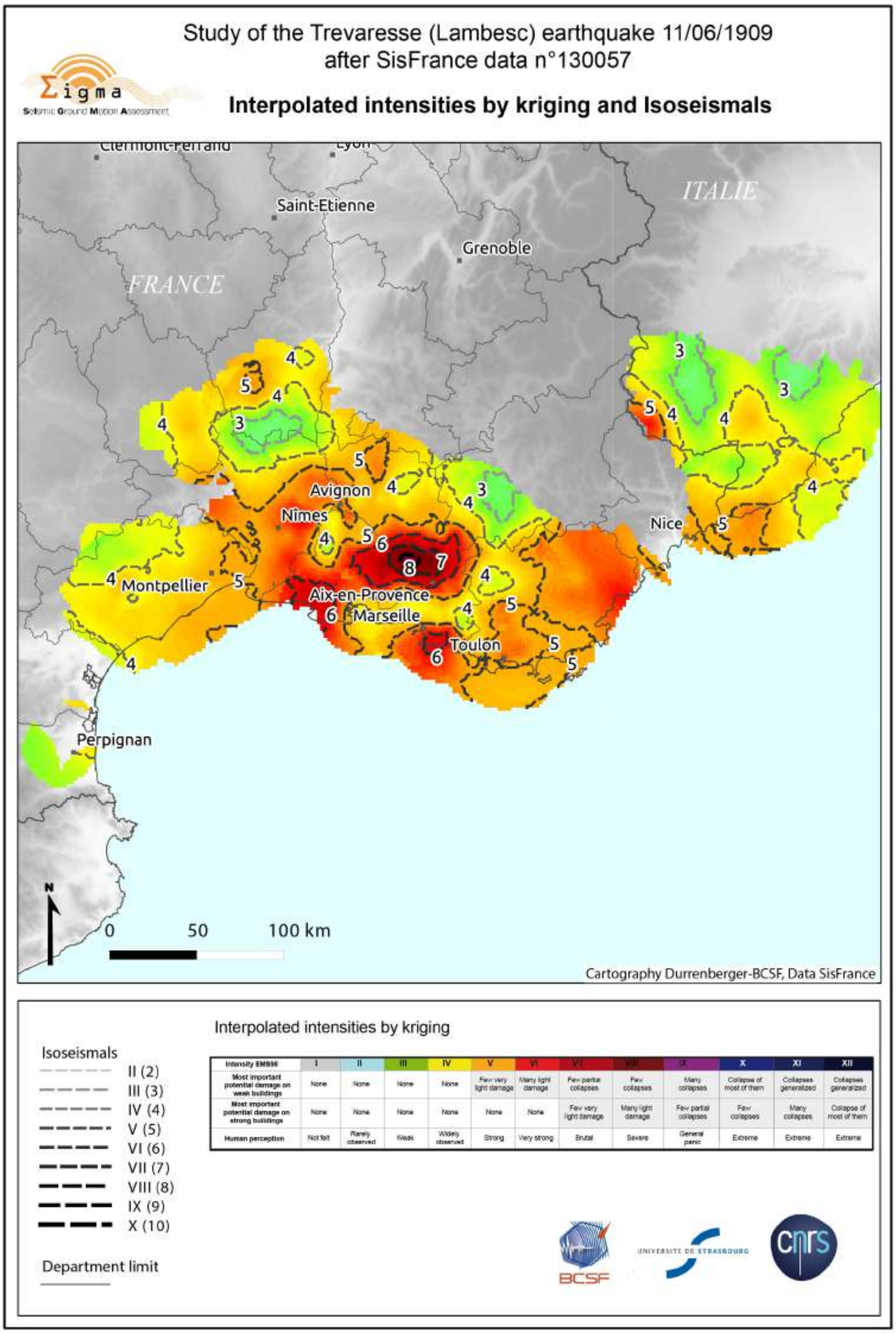


Observed intensity
- II (2)
- III (3)
- IV (4)
- V (5)
- VI (6)
- VII (7)
- VIII (8)
- IX (9)
- X+ (10)

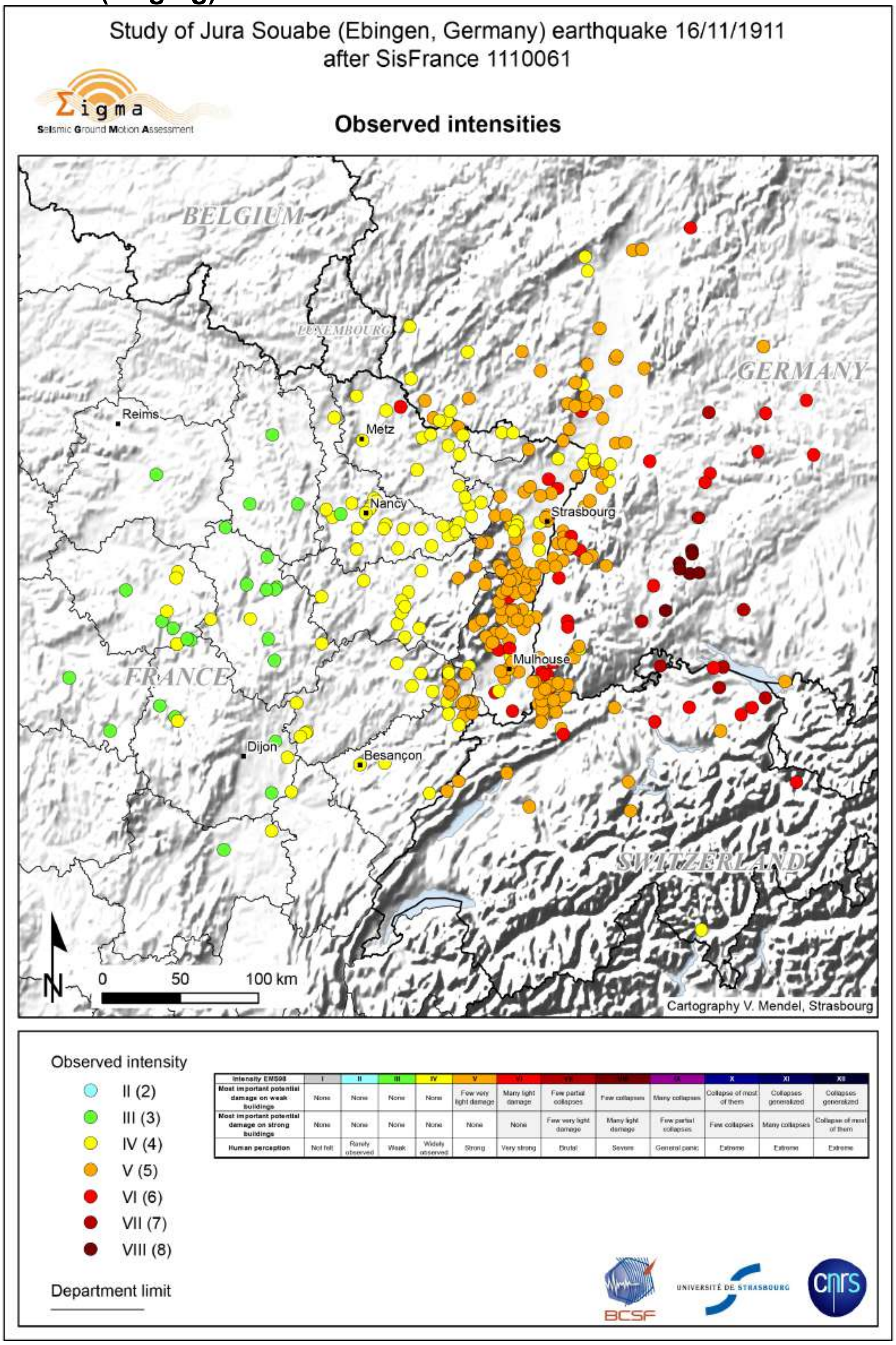
Department limit

Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme


Study of the Trevaresse (Lambesc) earthquake 11/06/1909
after SisFrance data n°130057
Interpolated intensities by kriging and Isoseismals
Clermont-Ferrand
Lyon
Saint-Etienne
Grenoble
ITALIE
FRANCE
Avignon
Nimes
Montpellier
Aix-en-Provence
Marseille
Toulon
Nice
Perpignan
N
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Isoseismals
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98: I, II, III, IV, V, VI, VII, VIII, IX, X, XI, XII
Most important potential damage on weak buildings: None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them, Collapses generalized, Collapses generalized
Most important potential damage on strong buildings: None, None, None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them
Human perception: Not felt, Rarely observed, Weak, Widely observed, Strong, Very strong, Brutal, Severe, General panic, Extreme, Extreme, Extreme
BCSF
UNIVERSITÉ DE STRASBOURG
cnrs

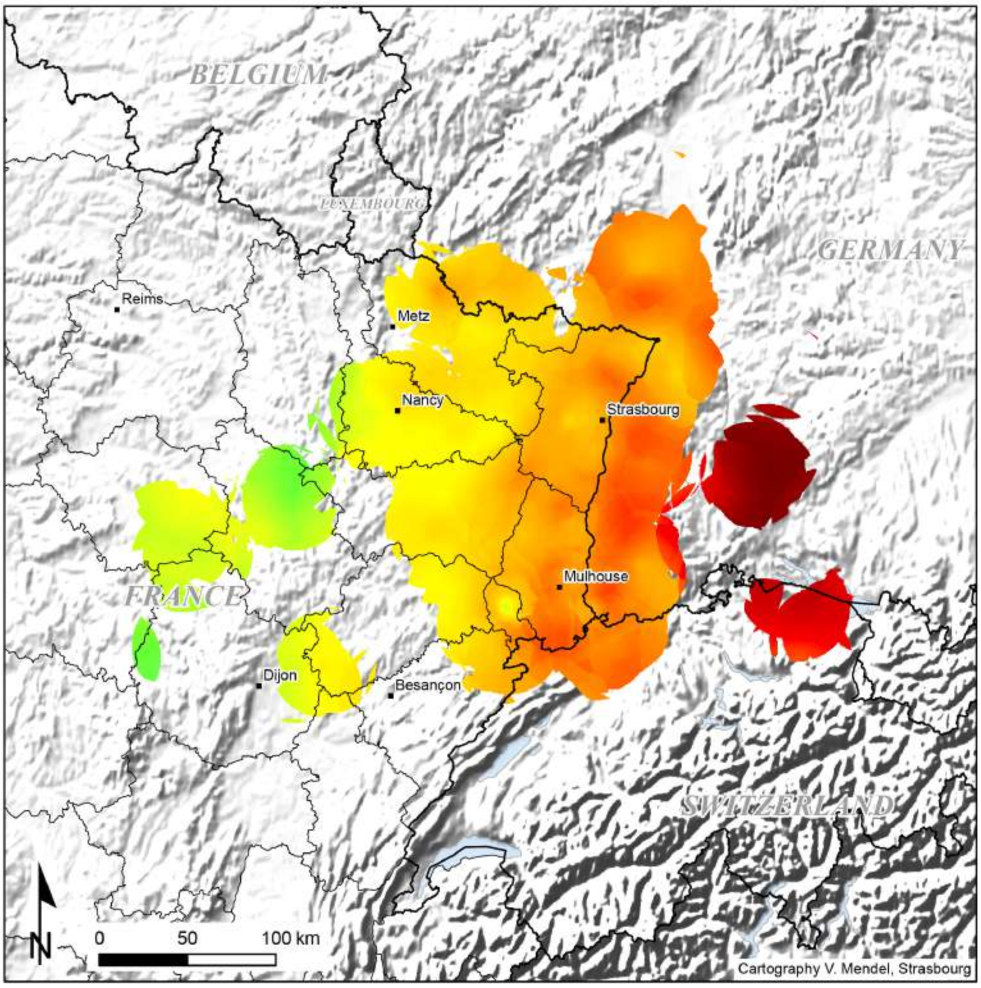
1911-11-16: Jura Souabe earthquake (auto), Mw=5.5, Depth=4km, Isoseismal-min (Kriging)=none



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Jura Souabe (Ebingen, Germany) earthquake 16/11/1911
after SisFrance 1110061

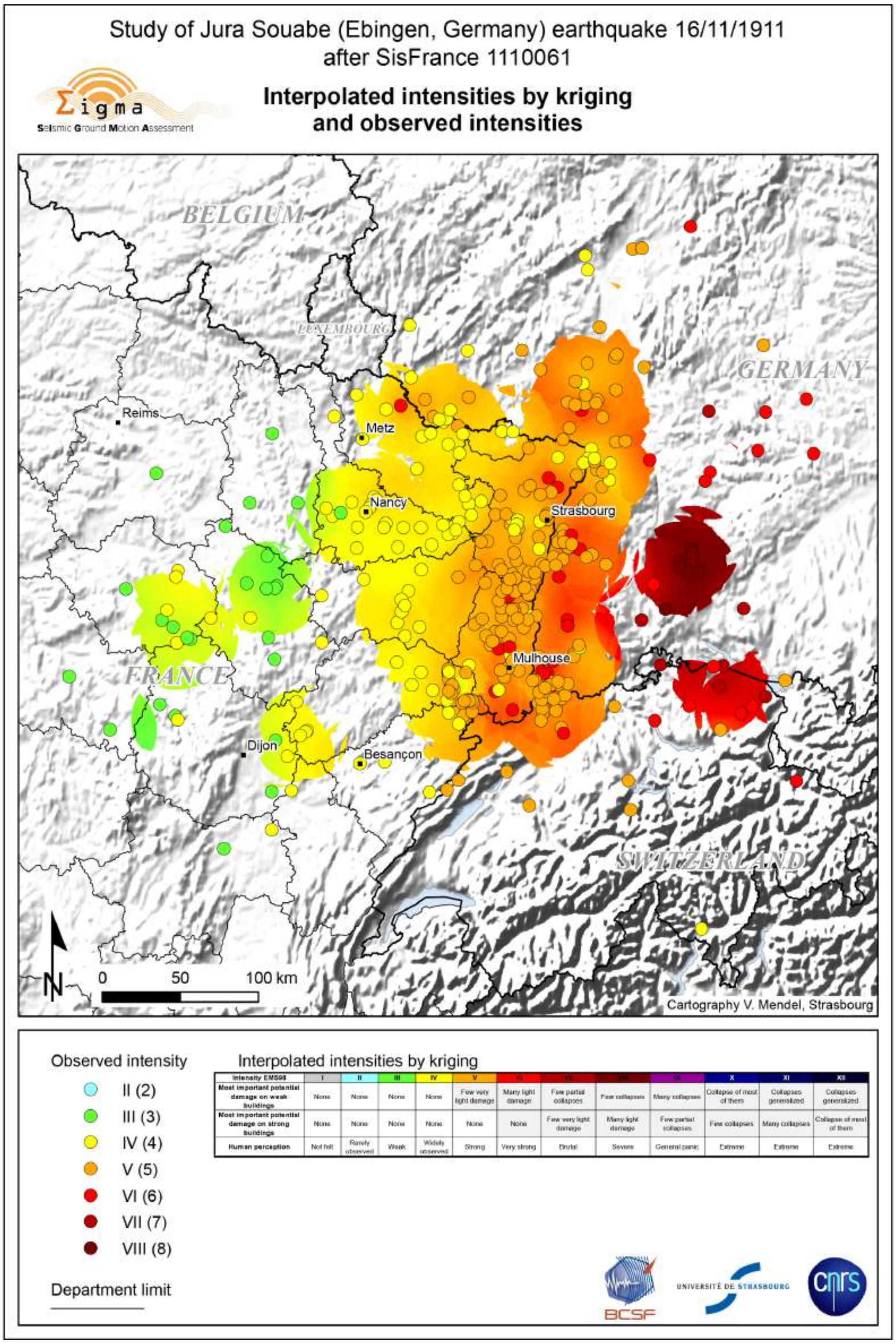
Interpolated intensities by kriging



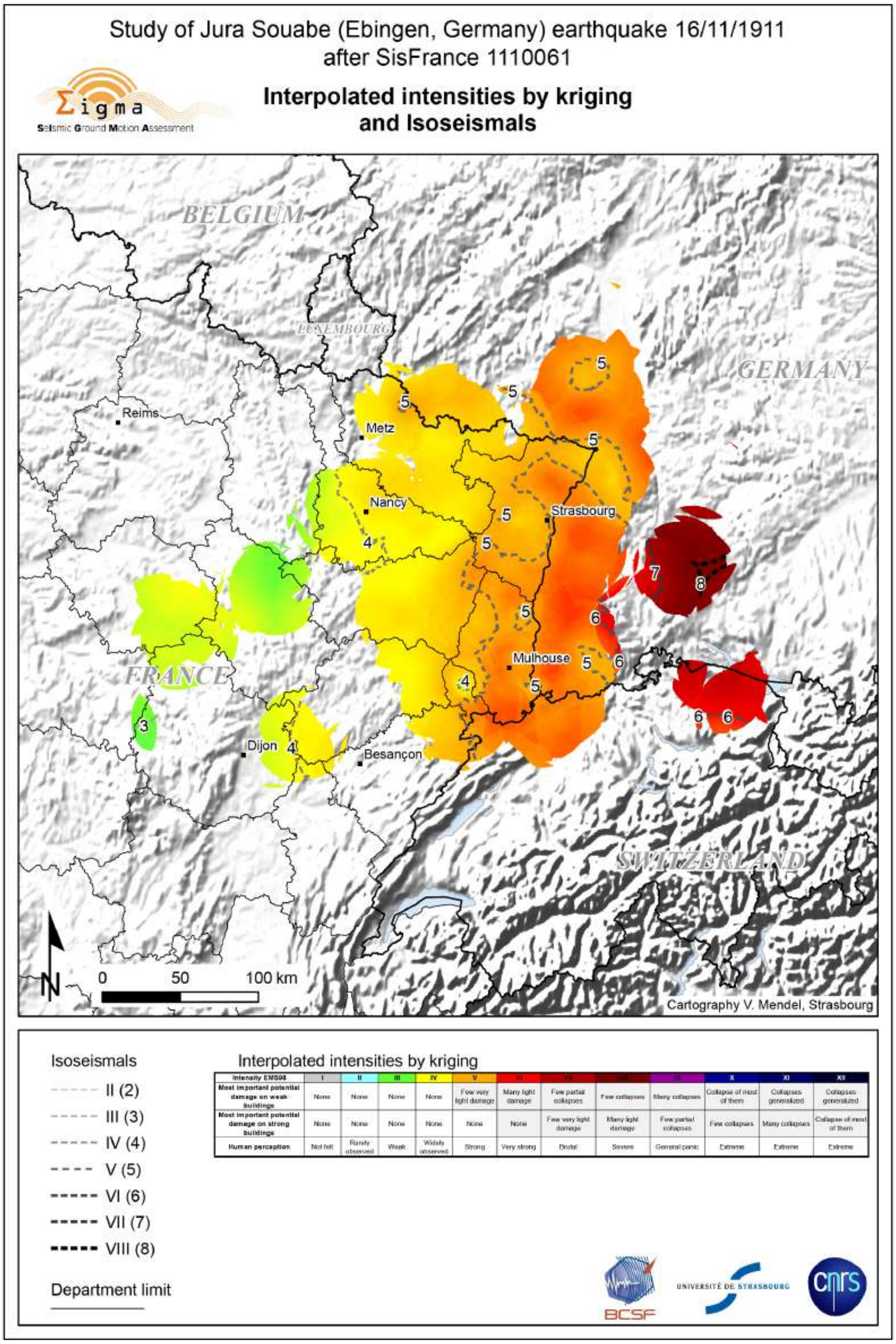
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

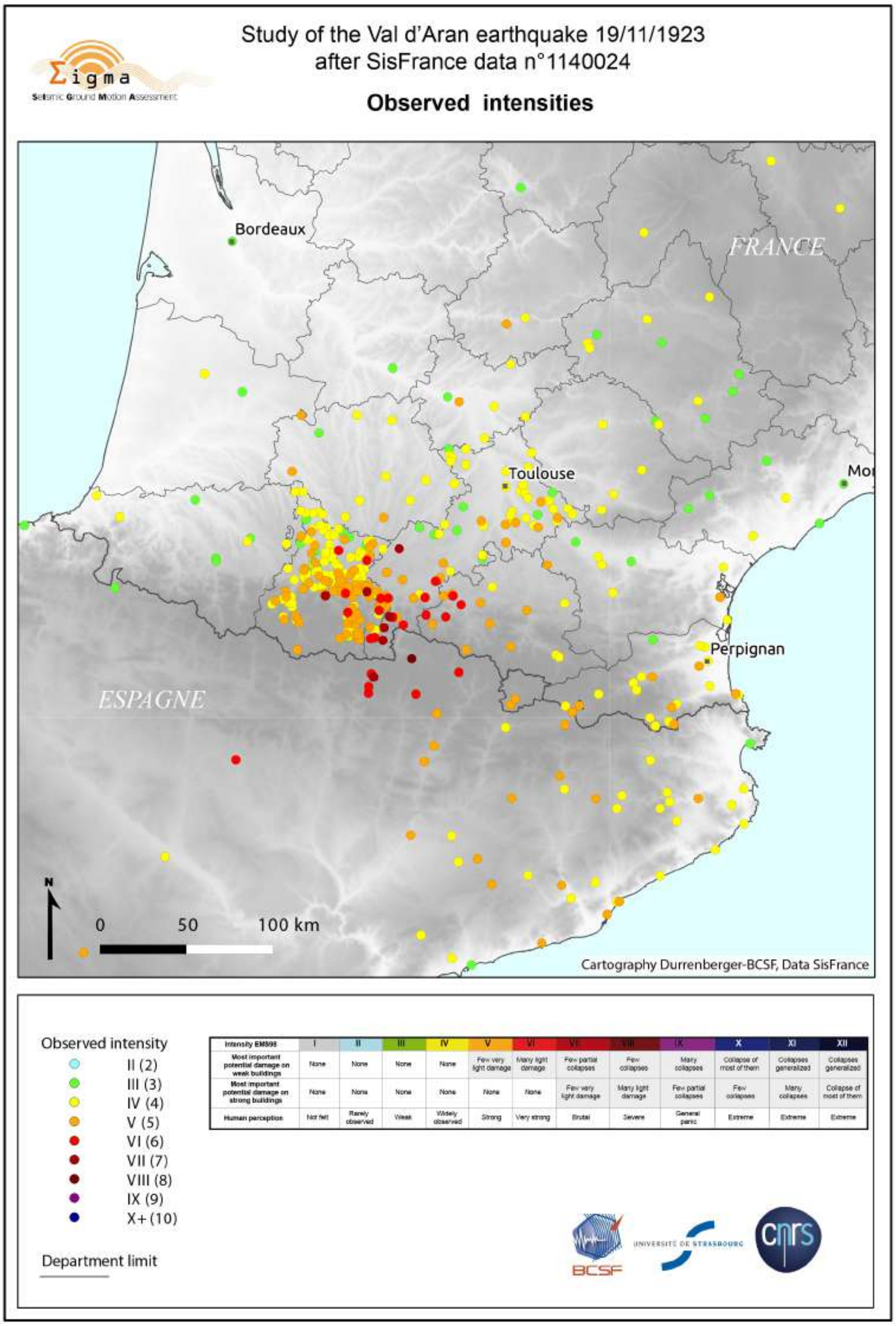


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

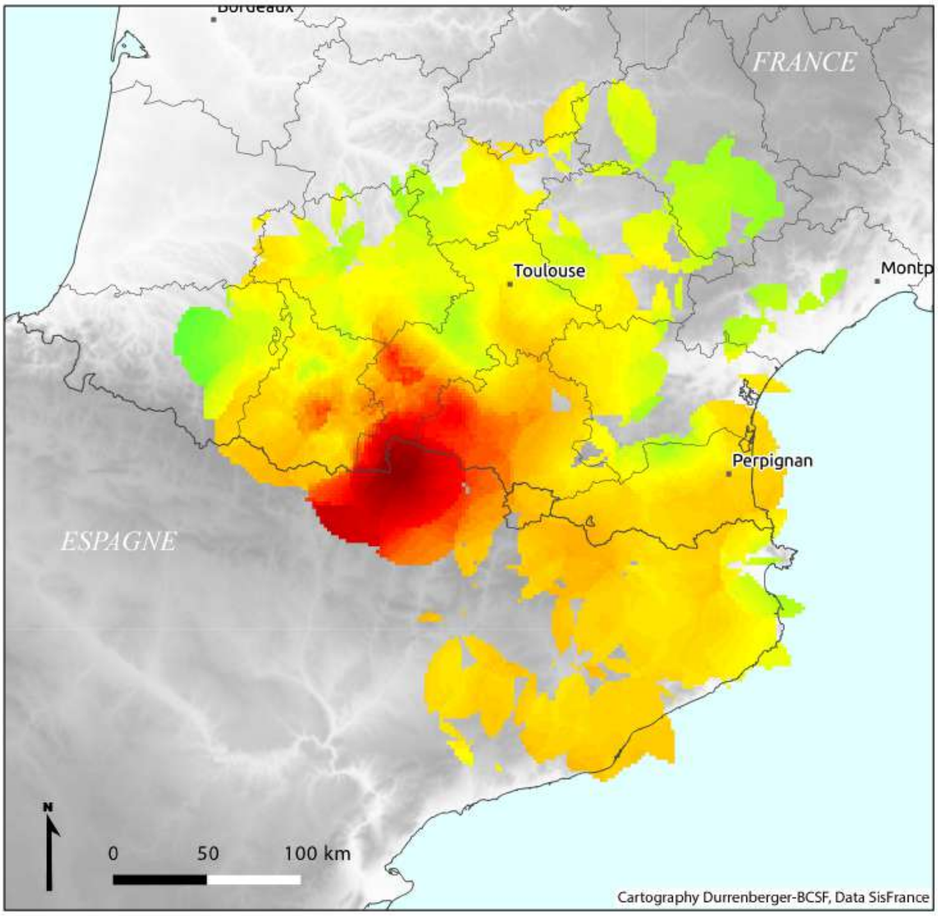
1923-11-19: Val d'Aran earthquake, Mw=5.4, Depth=5km, Isoseismal-min (Kriging)=5.0



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of the Val d'Aran earthquake 19/11/1923
after SisFrance data n°1140024

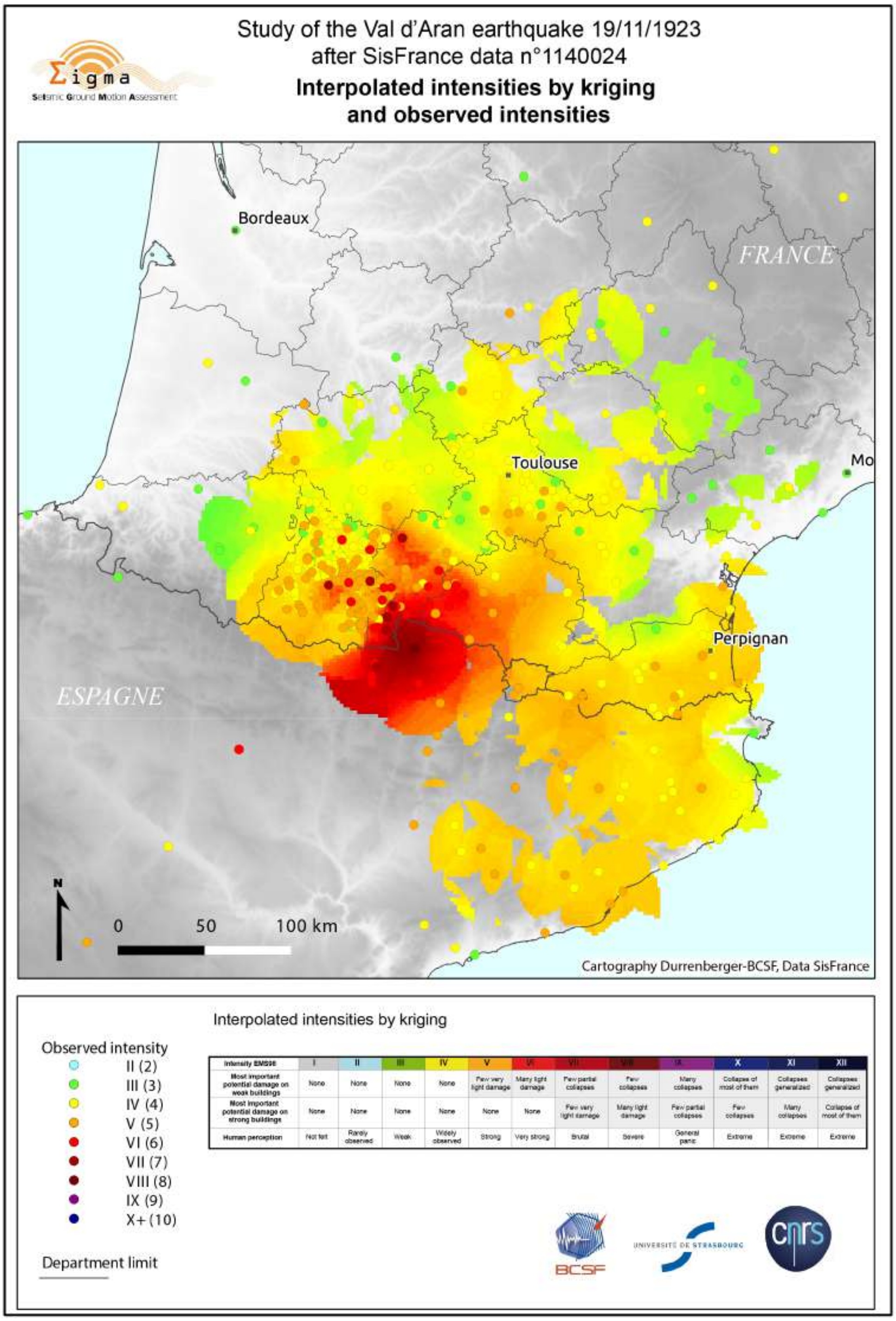
Interpolated intensities by kriging



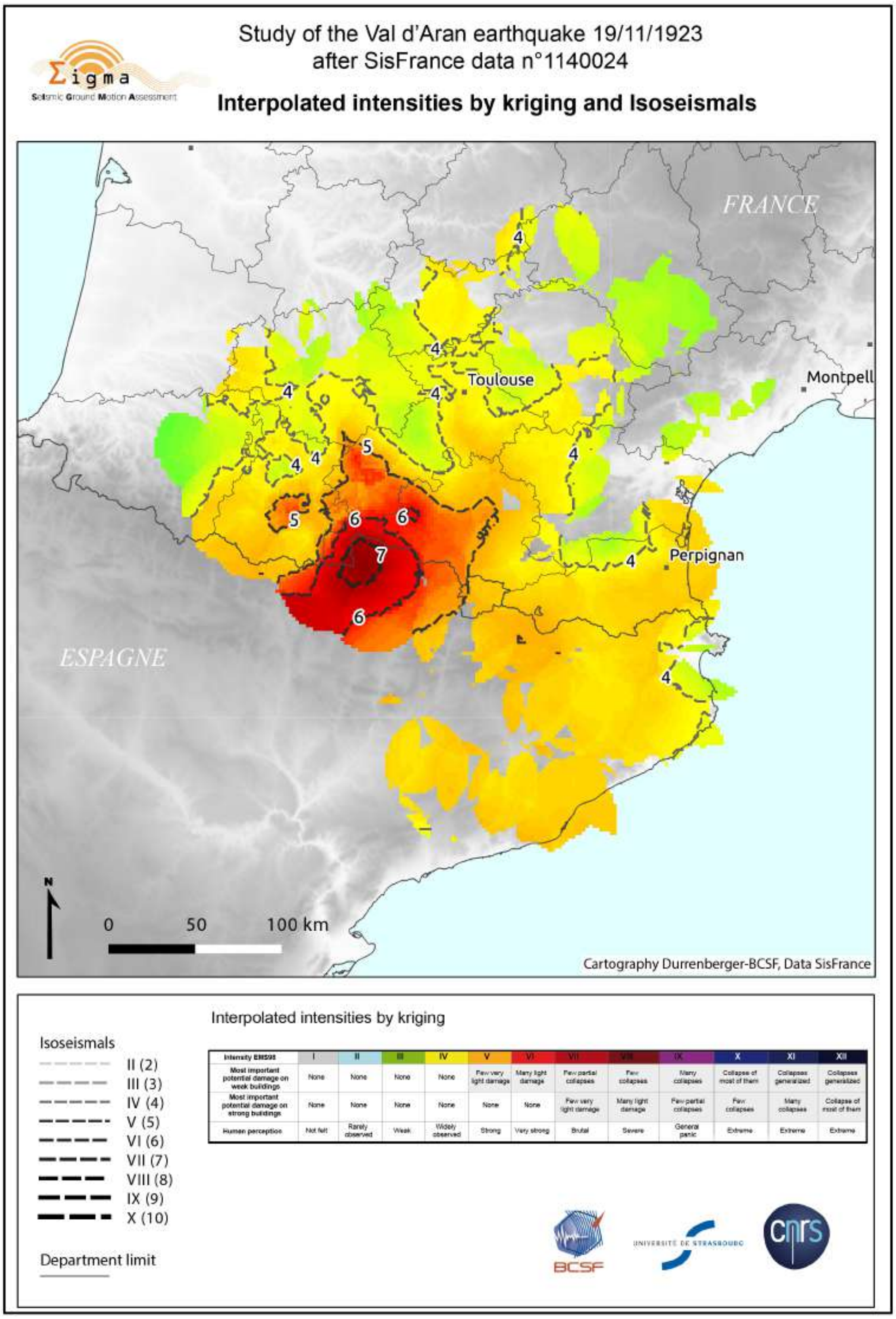
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme


Study of the Val d'Aran earthquake 19/11/1923
after SisFrance data n°1140024
Interpolated intensities by kriging and Isoseismals
Σigma
Seismic Ground Motion Assessment
FRANCE
Toulouse
Montpell
Perpignan
ESPAGNE
4
5
6
7
N
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Isoseismals
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98: I, II, III, IV, V, VI, VII, VIII, IX, X, XI, XII
Most important potential damage on week buildings: None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them, Collapses generalized, Collapses generalized
Most important potential damage on strong buildings: None, None, None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them
Human perception: Not felt, Rarely observed, Weak, Widely observed, Strong, Very strong, Brutal, Severe, General panic, Extreme, Extreme, Extreme
BCSF
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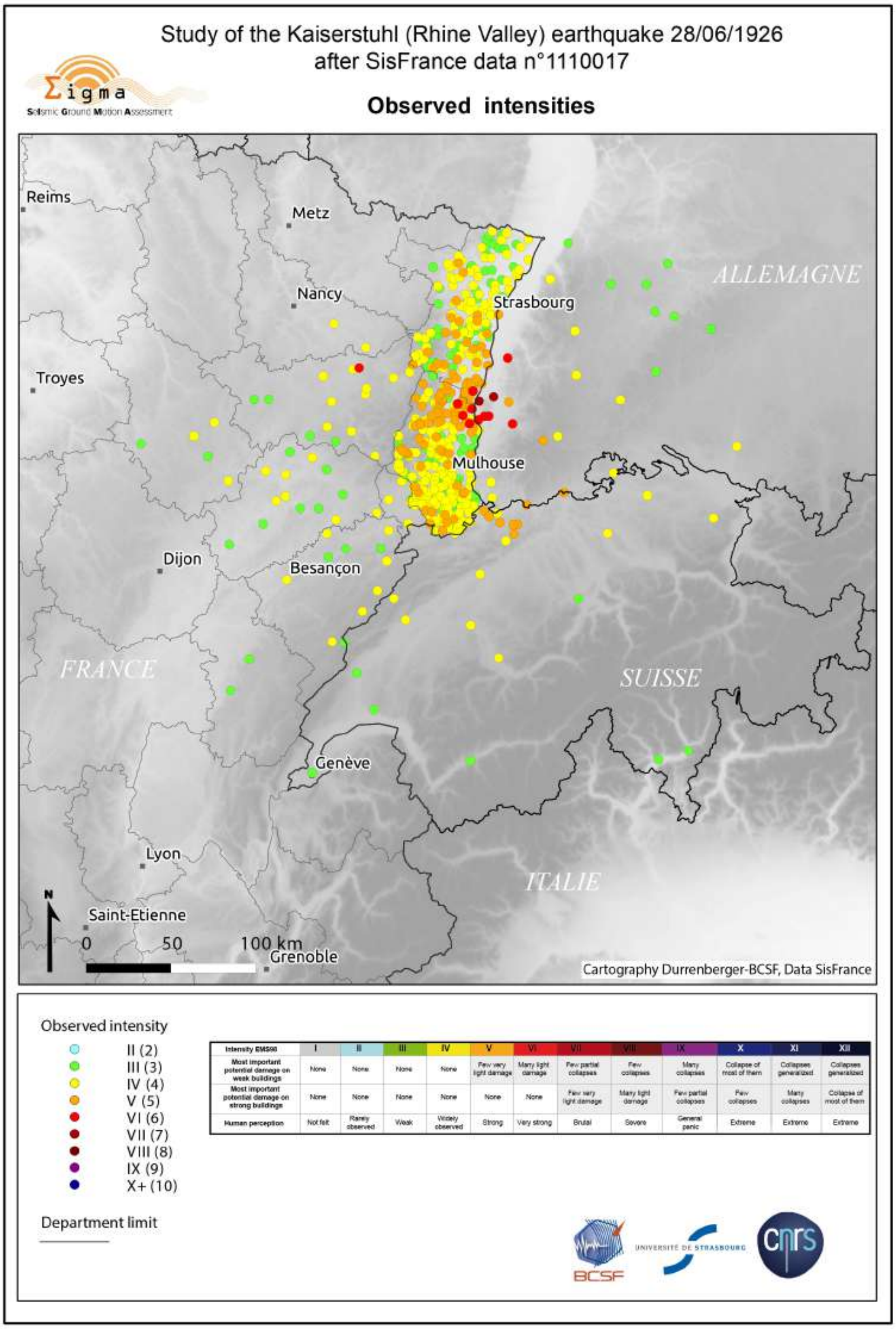
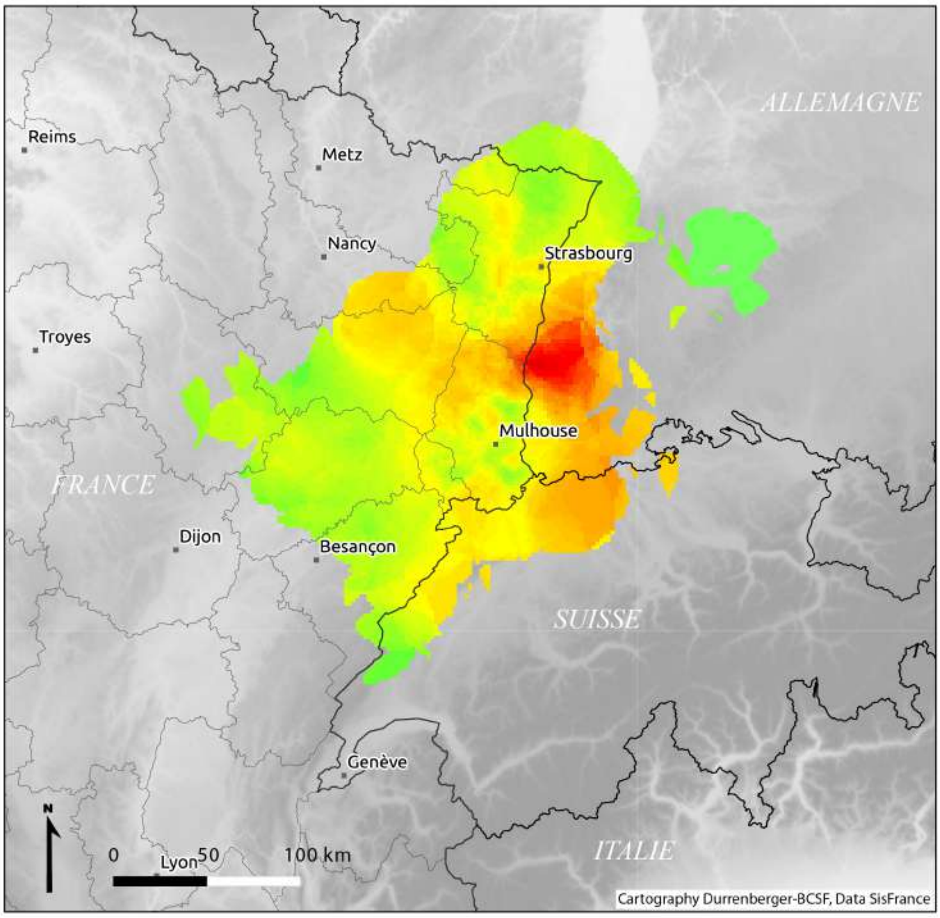
cnrs

1926-06-28: Kaiserstuhl earthquake, Mw=5, Depth=15km, Isoseismal-min (Kriging)=4.5



Study of the Kaiserstuhl (Rhine Valley) earthquake 28/06/1926
after SisFrance data n°1110017

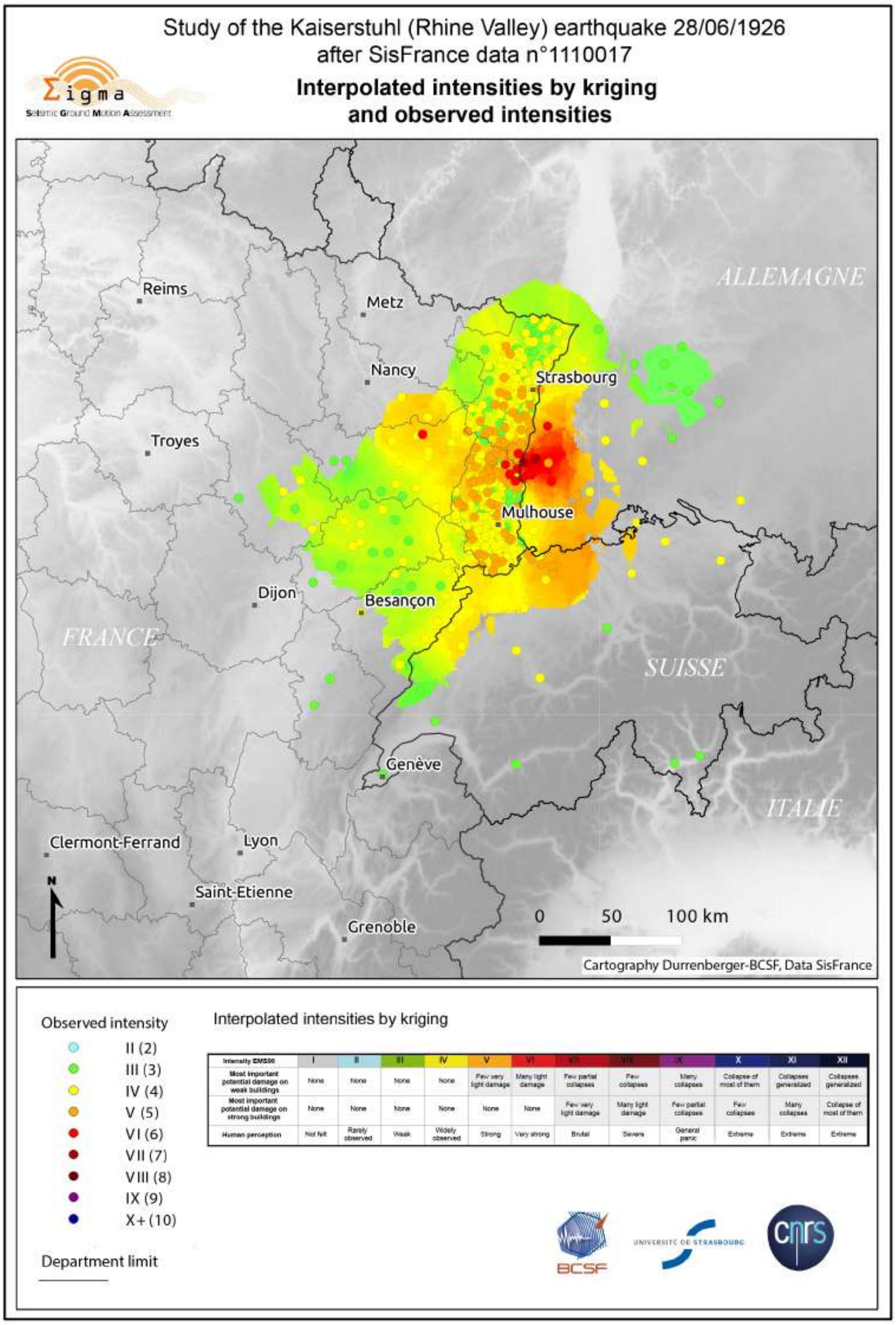
Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit


Study of the Kaiserstuhl (Rhine Valley) earthquake 28/06/1926
after SisFrance data n°1110017
Interpolated intensities by kriging
and observed intensities
ALLEMAGNE
Reims
Metz
Nancy
Strasbourg
Troyes
Mulhouse
Dijon
Besançon
FRANCE
SUISSE
Genève
ITALIE
Clermont-Ferrand
Lyon
Saint-Etienne
Grenoble
N
0 50 100 km
Cartography Durrenberger-BCSF, Data SisFrance
Observed intensity
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X+ (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98 | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII
Most important potential damage on weak buildings | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them | Collapses generalized | Collapses generalized
Most important potential damage on strong buildings | None | None | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them
Human perception | Not felt | Rarely observed | Weak | Widely observed | Strong | Very strong | Brutal | Severe | General panic | Extreme | Extreme | Extreme
BCSF
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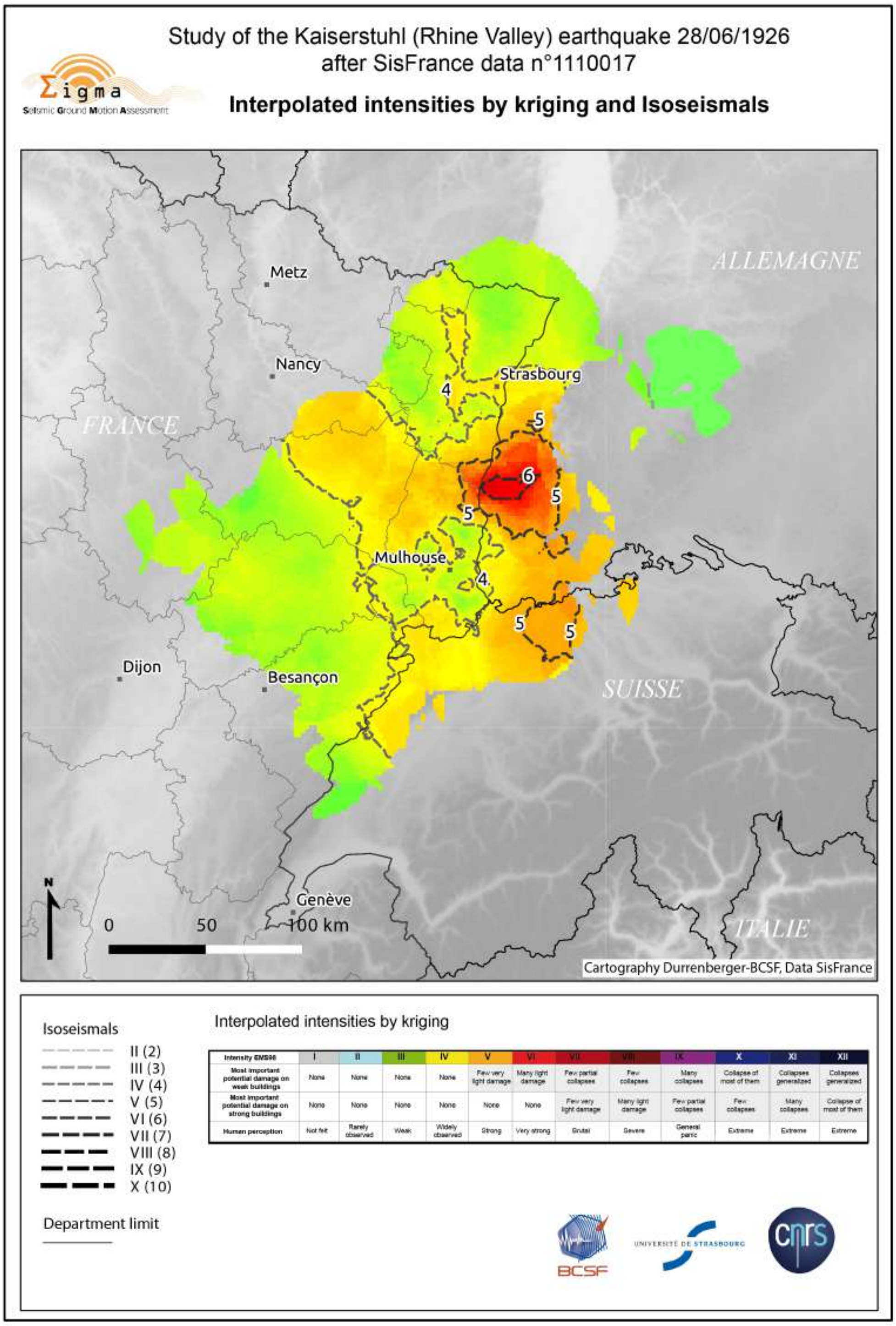
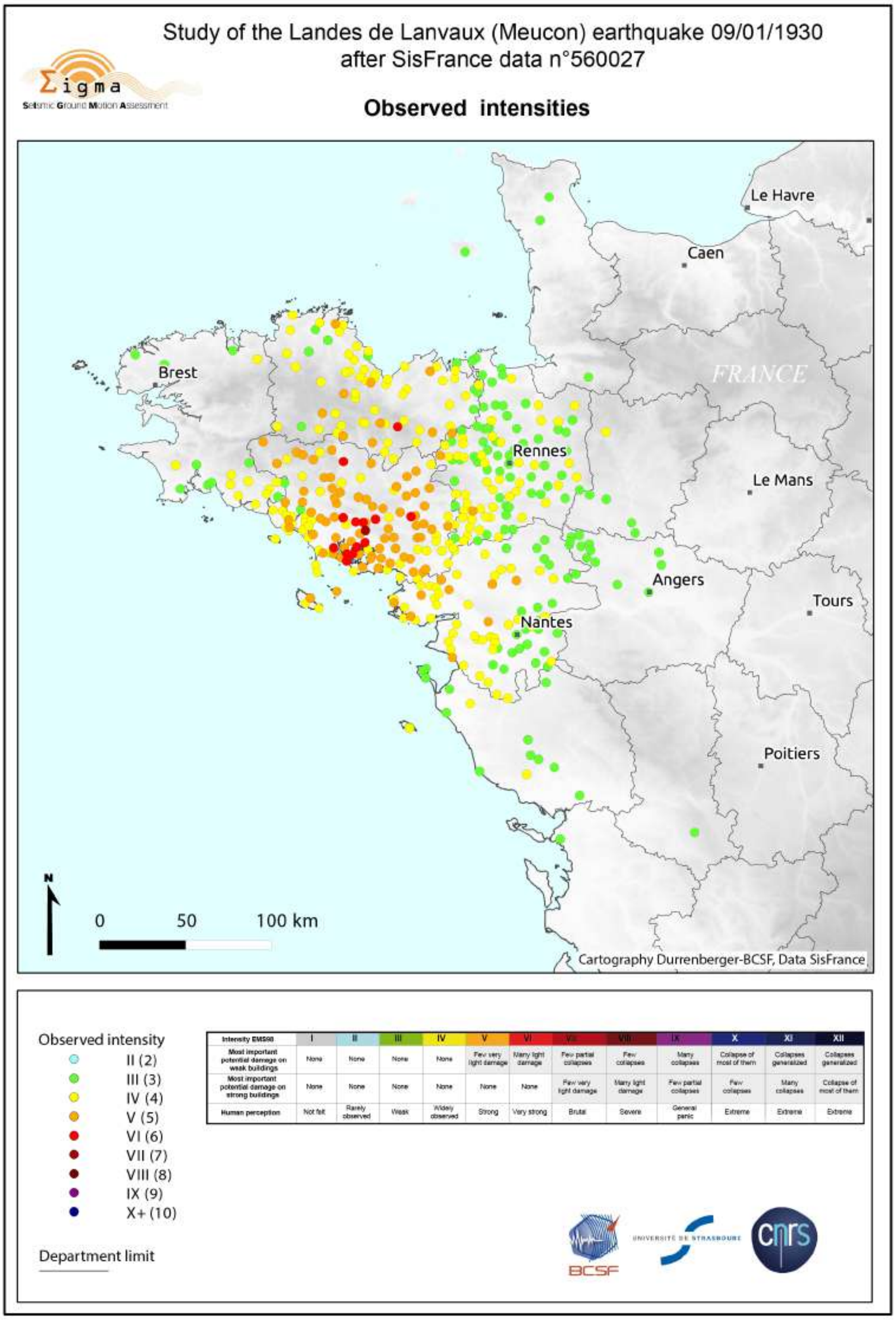


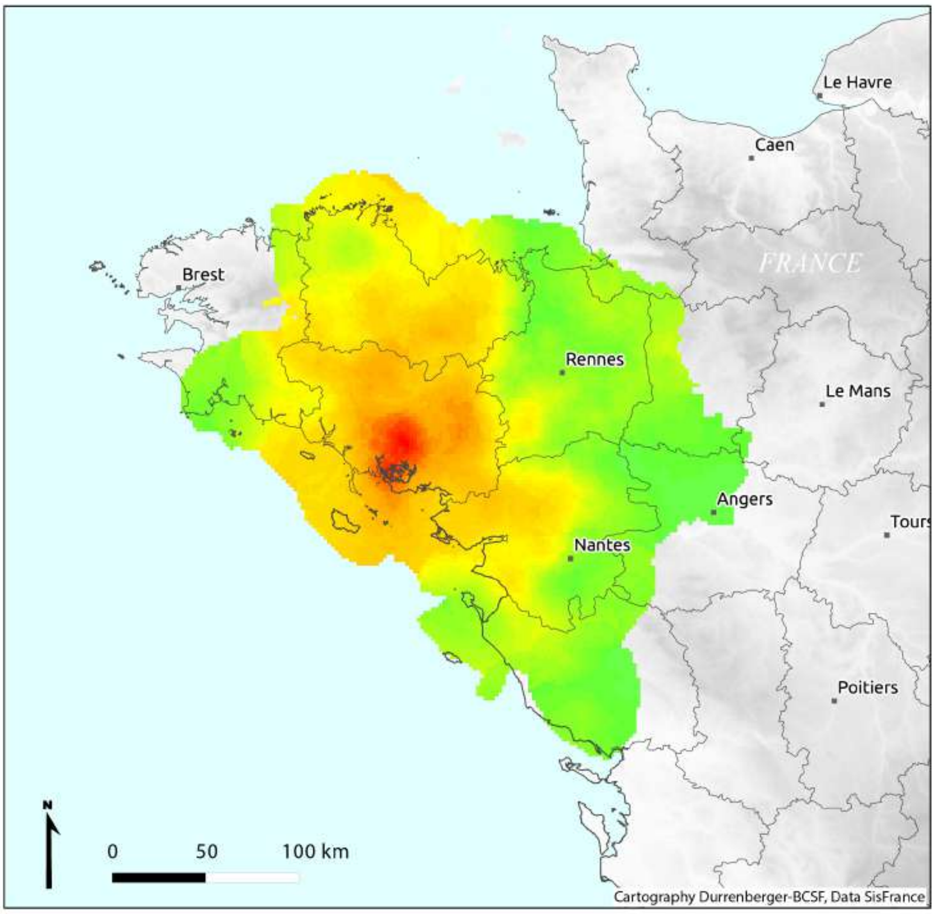
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1930-01-09: Landes de Lanvaux earthquake, Mw=5.4, Depth=5km, Isoseismal-min (Kriging)=4.0



Study of the Landes de Lanvaux (Meucon) earthquake 09/01/1930
after SisFrance data n°560027

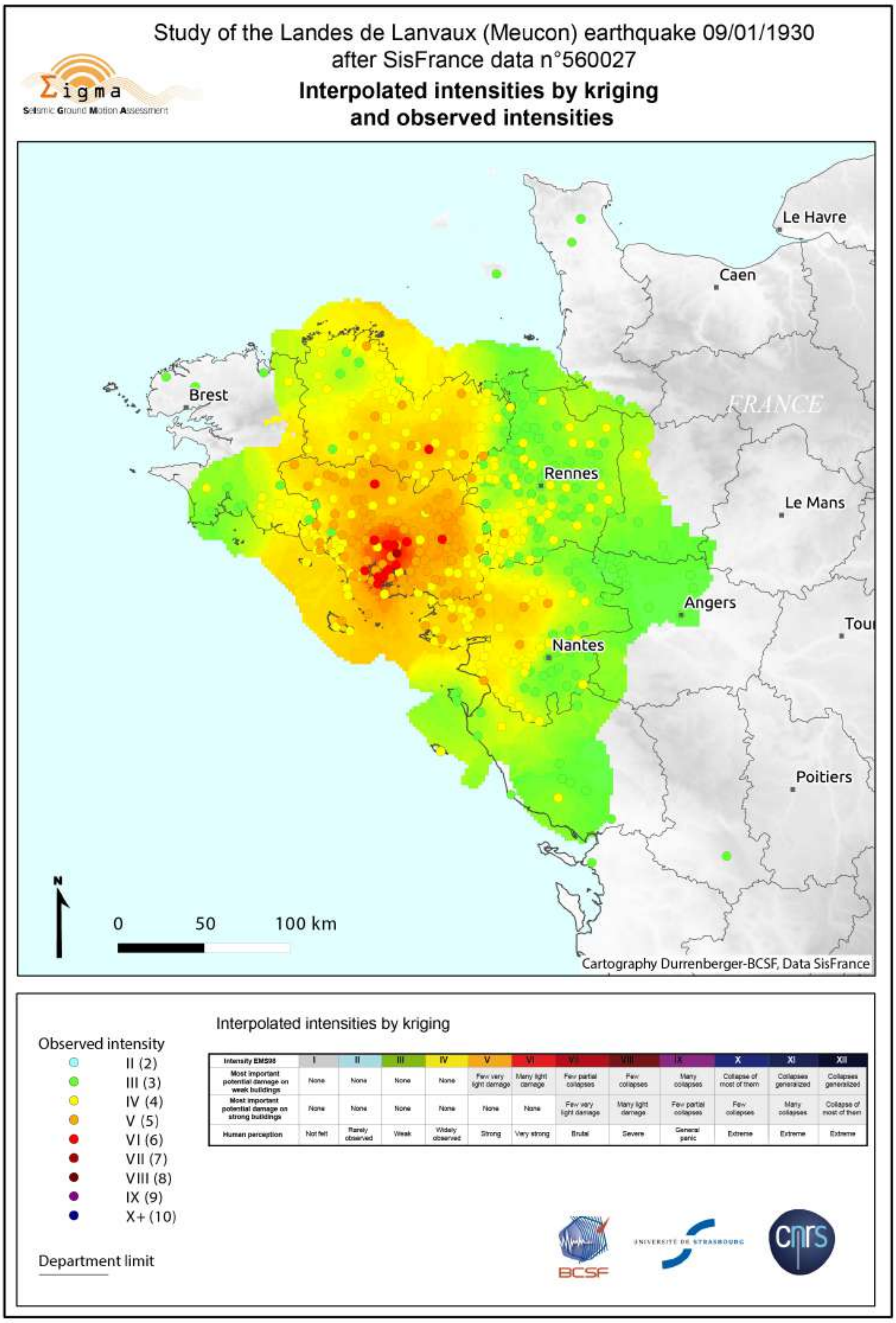
Interpolated intensities by kriging



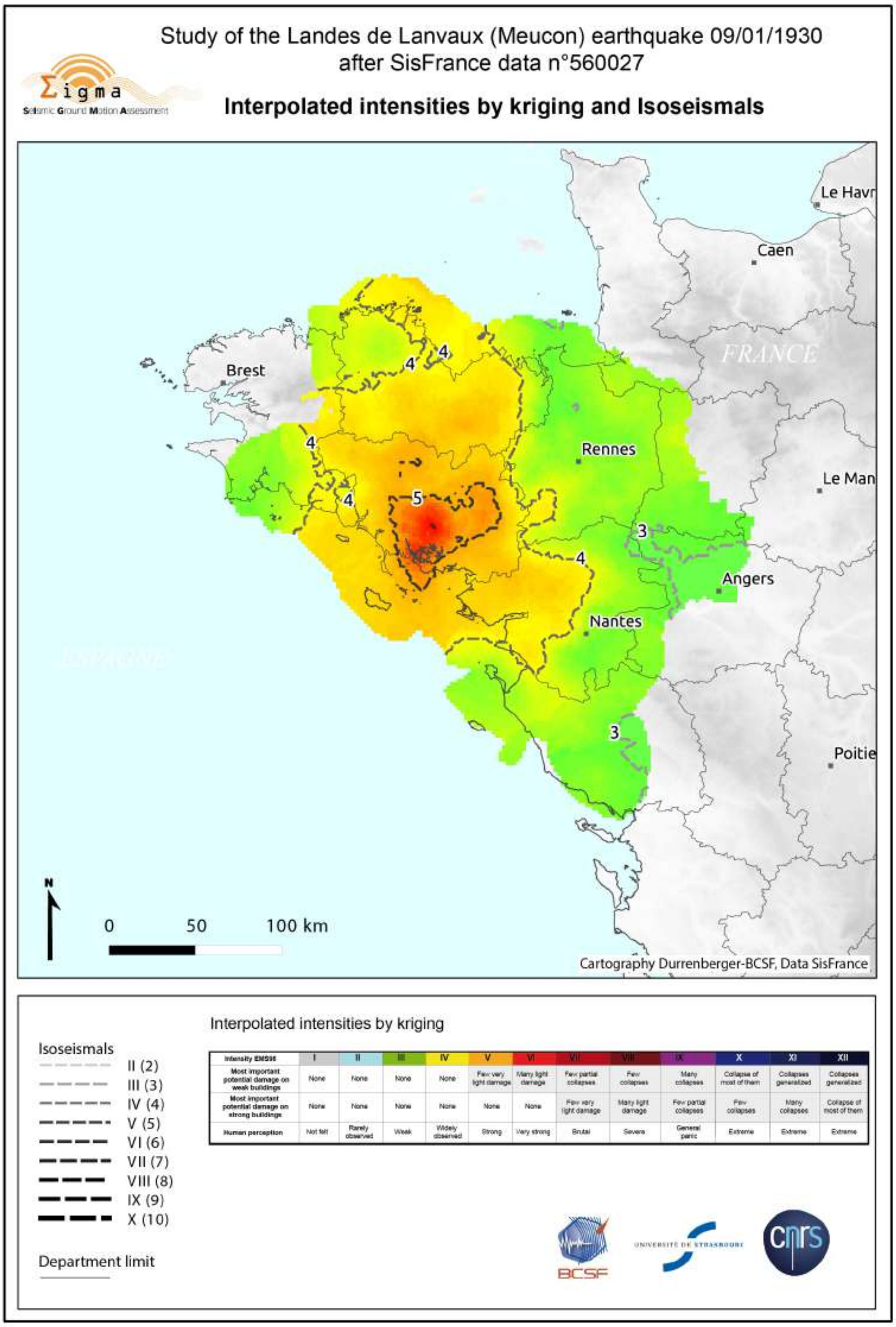
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

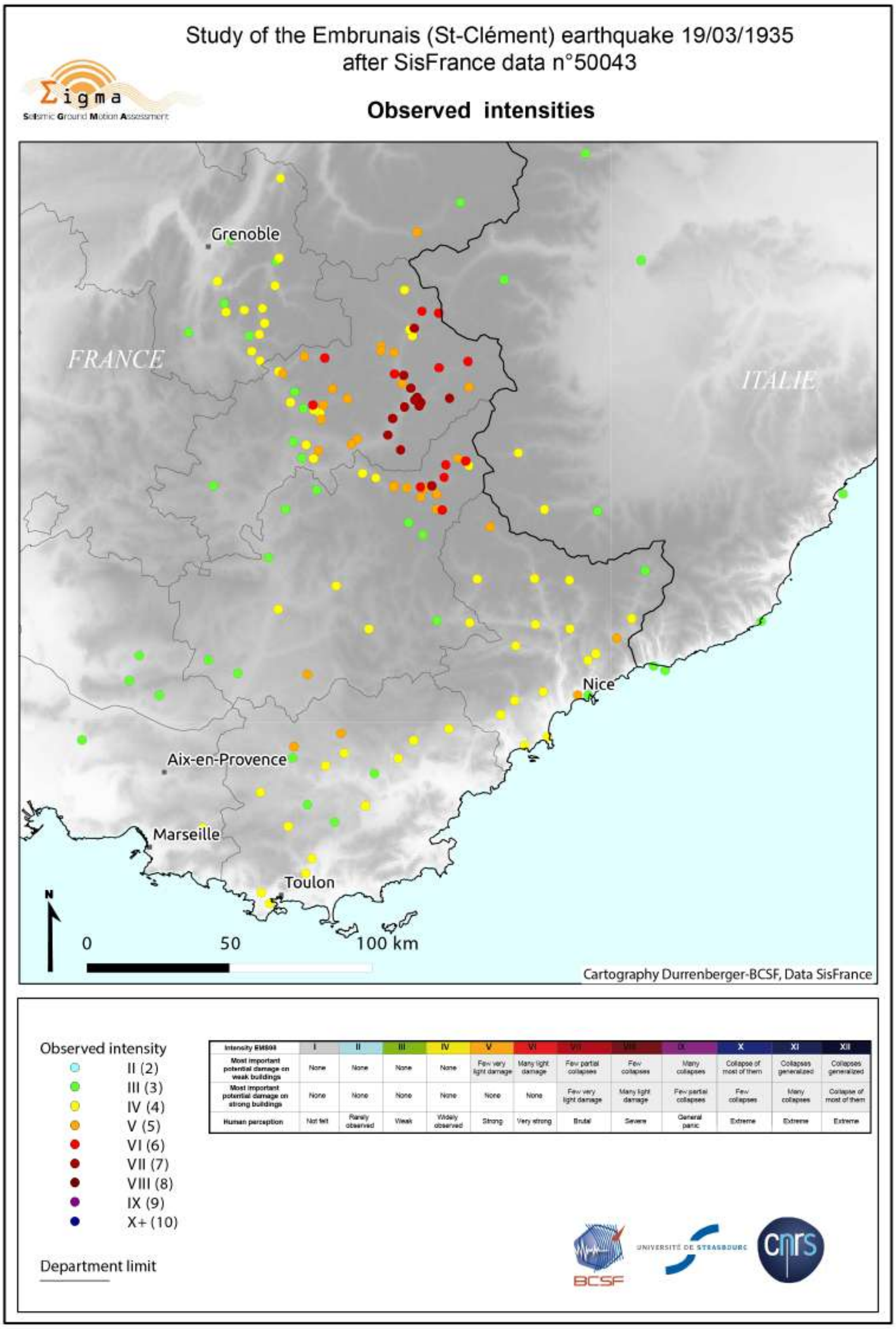


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



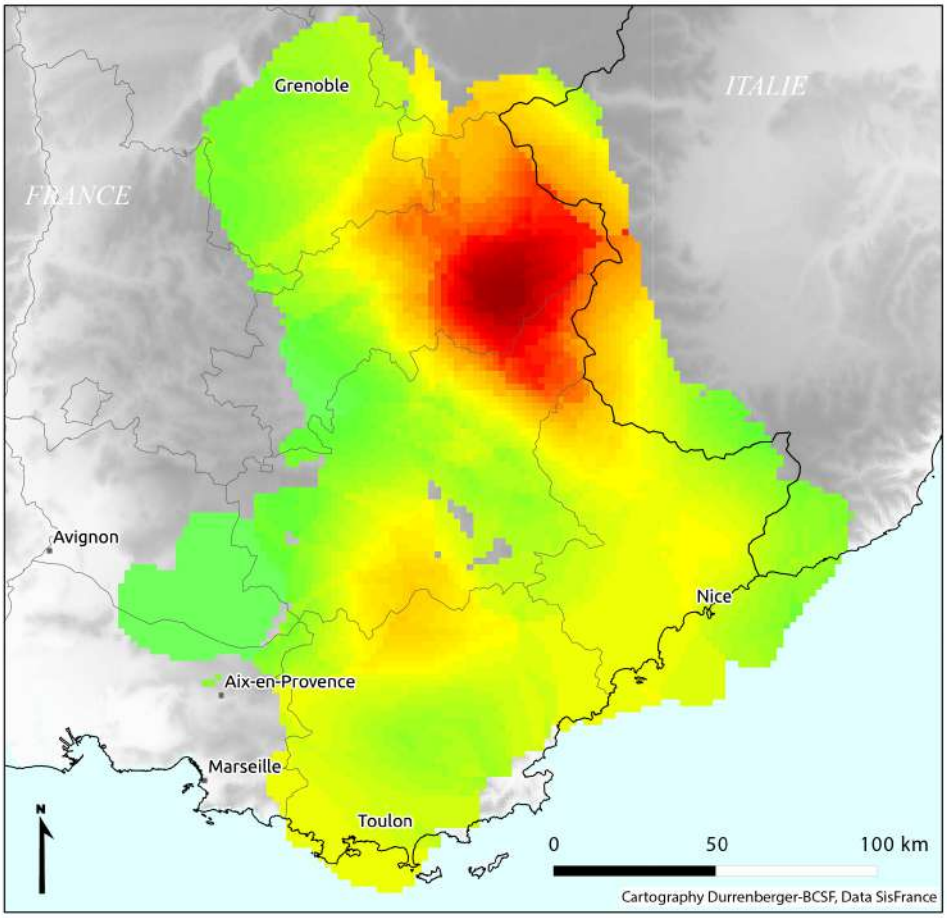
Study of the Landes de Lanvaux (Meucon) earthquake 09/01/1930
after SisFrance data n°560027
Interpolated intensities by kriging and Isoseismals
Σigma
Seismic Ground Motion Assessment
Le Havr
Caen
FRANCE
Brest
Rennes
Le Man
Angers
Nantes
Poitie
4
5
3
N
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Isoseismals
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98 | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII
Most important potential damage on weak buildings | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them | Collapses generalized | Collapses generalized
Most important potential damage on strong buildings | None | None | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them
Human perception | Not felt | Rarely observed | Weak | Widely observed | Strong | Very strong | Brutal | Severe | General panic | Extreme | Extreme | Extreme
BCSF
CNRS

1935-03-19: Embrunais earthquake, Mw=4.9, Depth=10km, Isoseismal-min (Kriging)=4.0



Study of the Embrunais (St-Clément) earthquake 19/03/1935
after SisFrance data n°50043

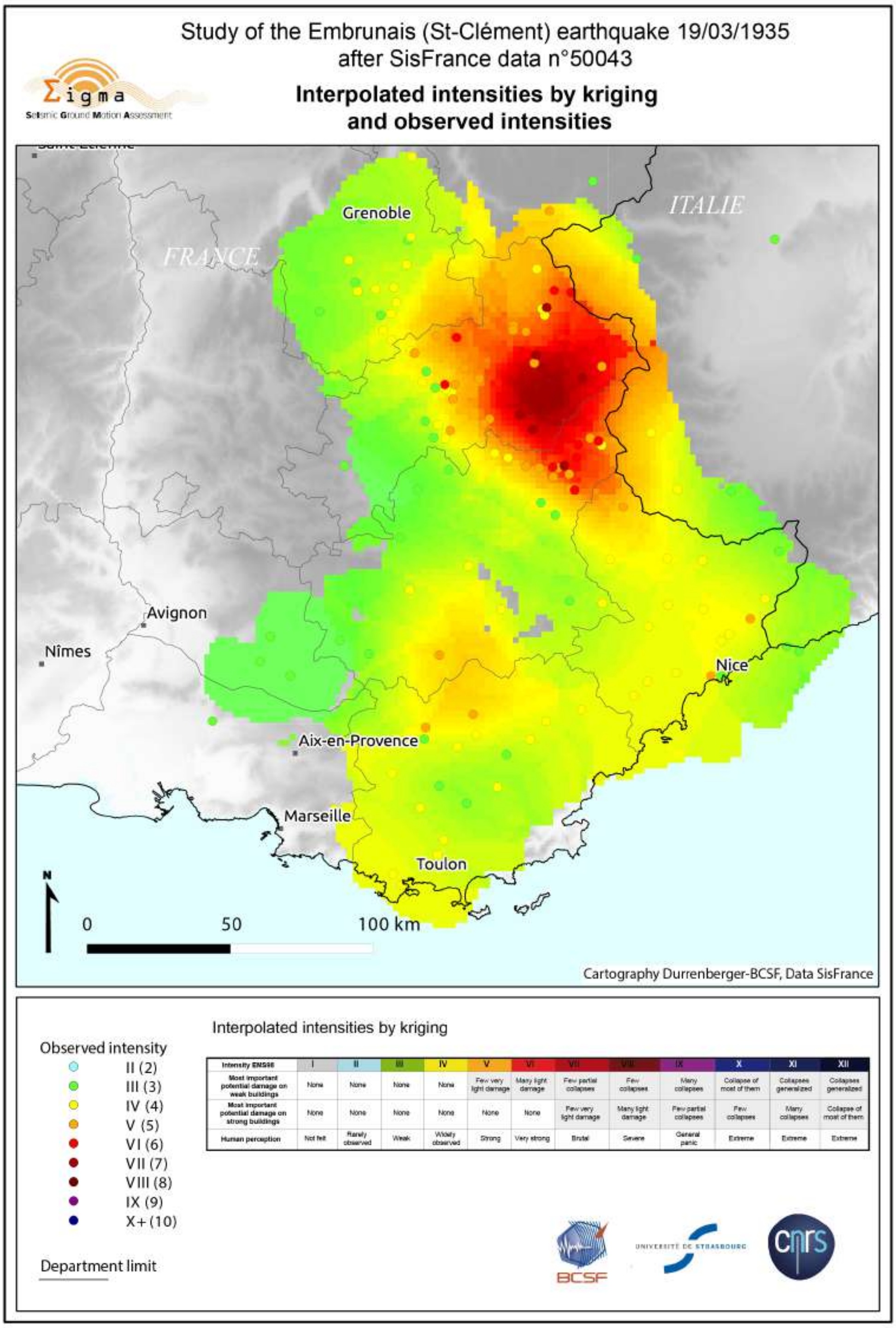
Interpolated intensities by kriging



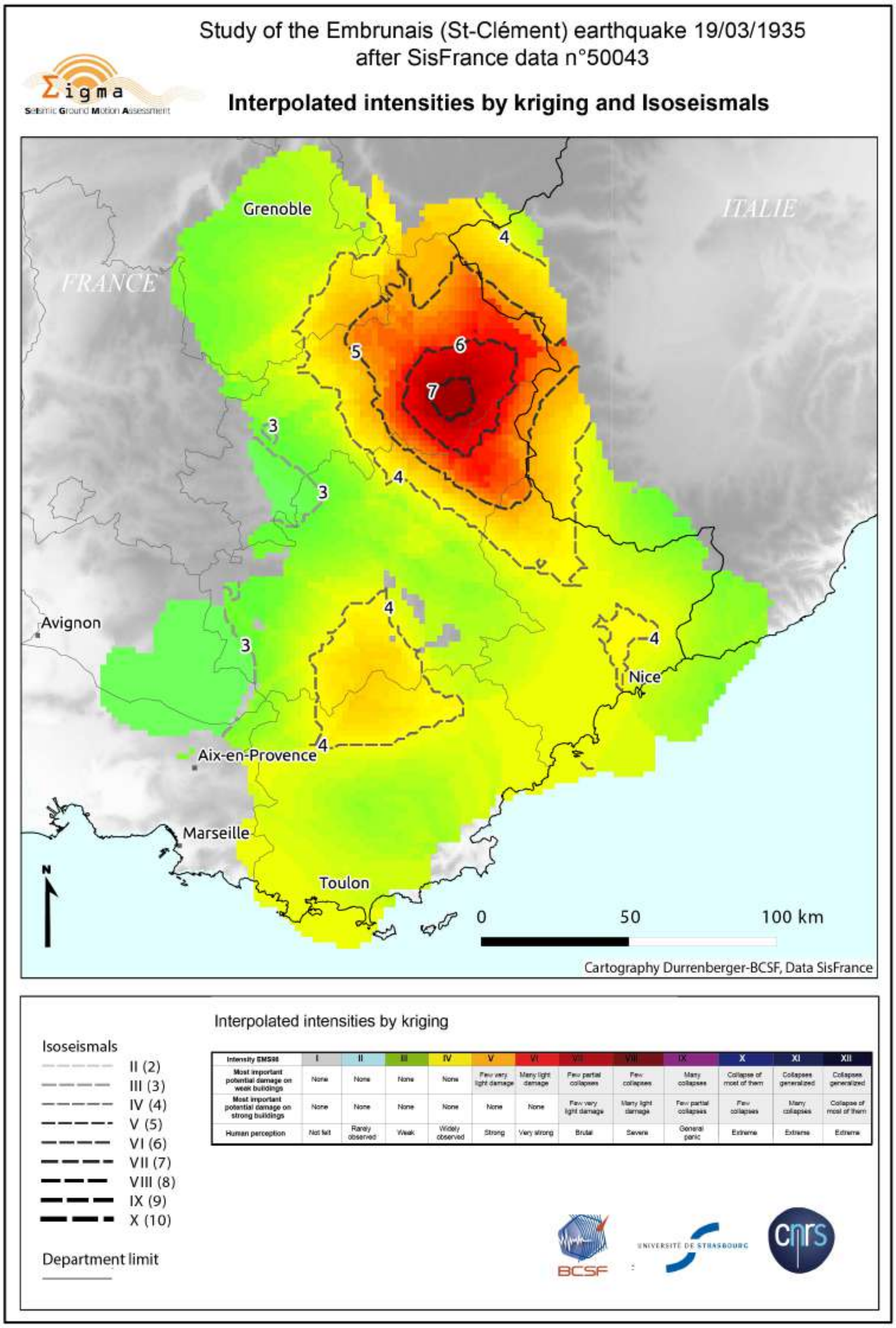
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

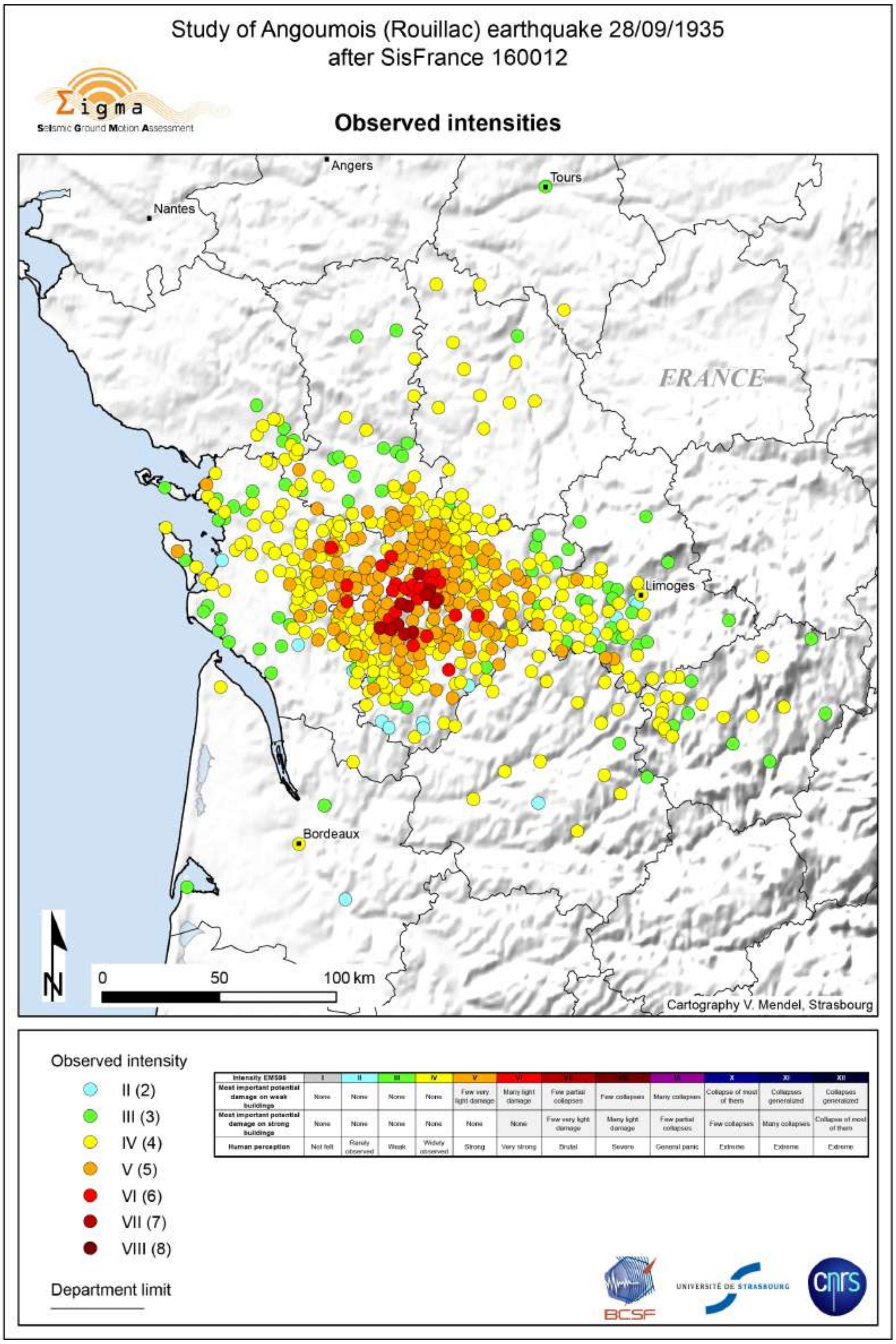


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

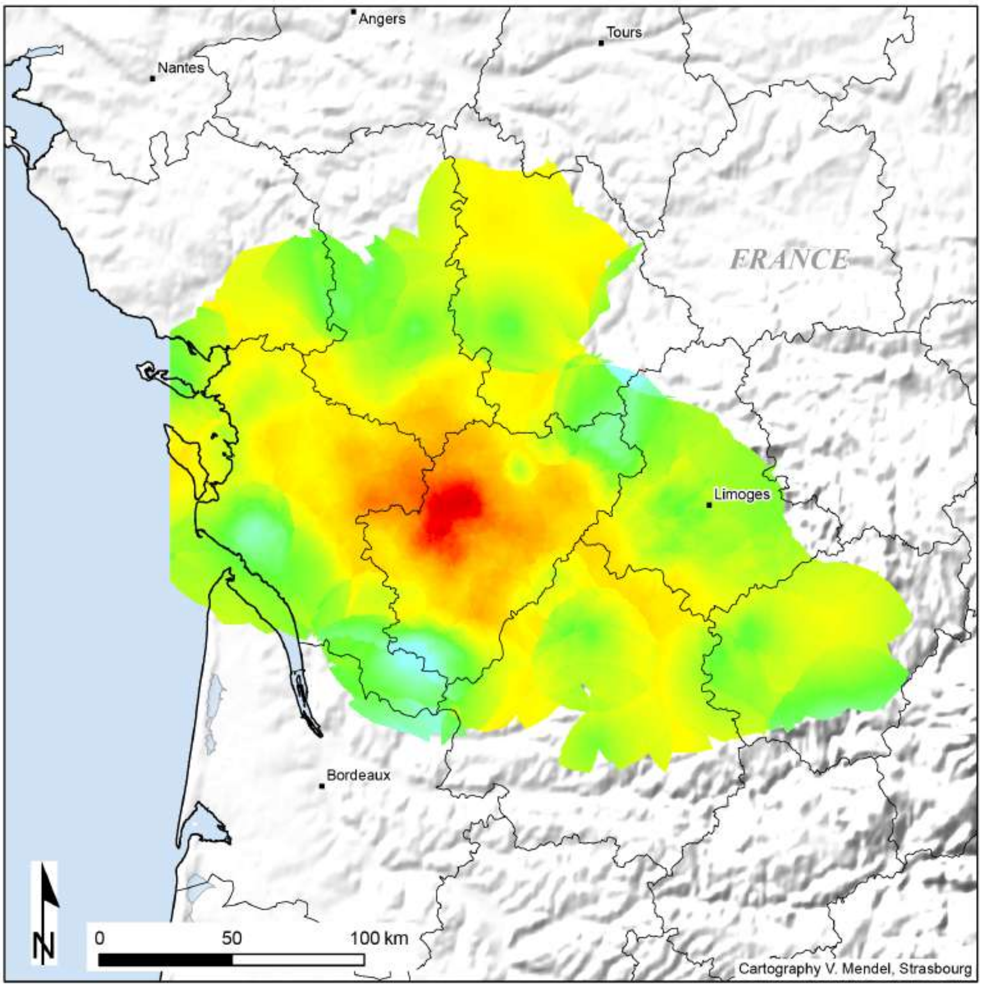
1935-09-28: Angoumois earthquake (auto), Mw=4.9, Depth=Unknown, Isoseismal-min (Kriging)=3.5



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Angoumois (Rouillac) earthquake 28/09/1935
after SisFrance 160012

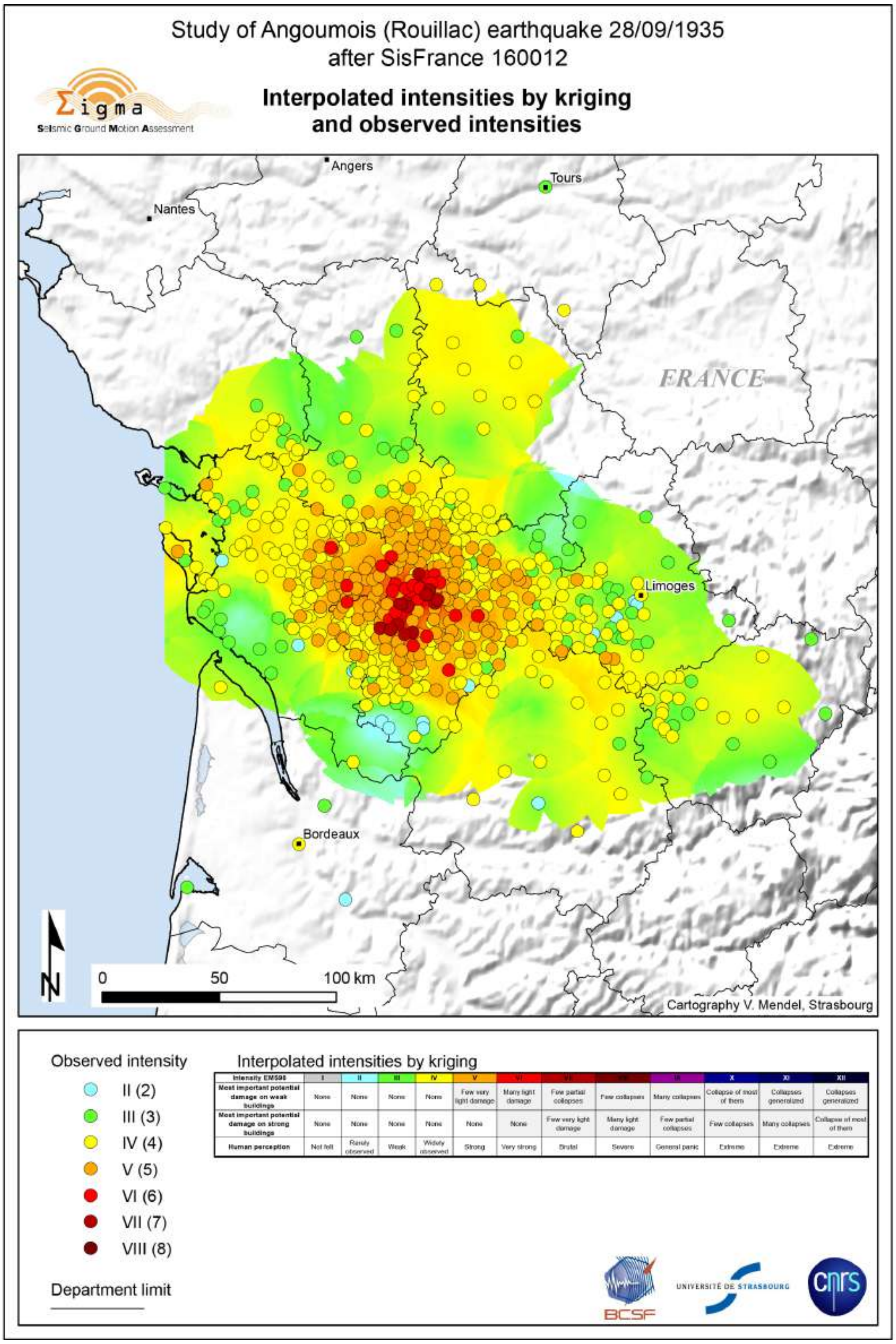
Interpolated intensities by kriging



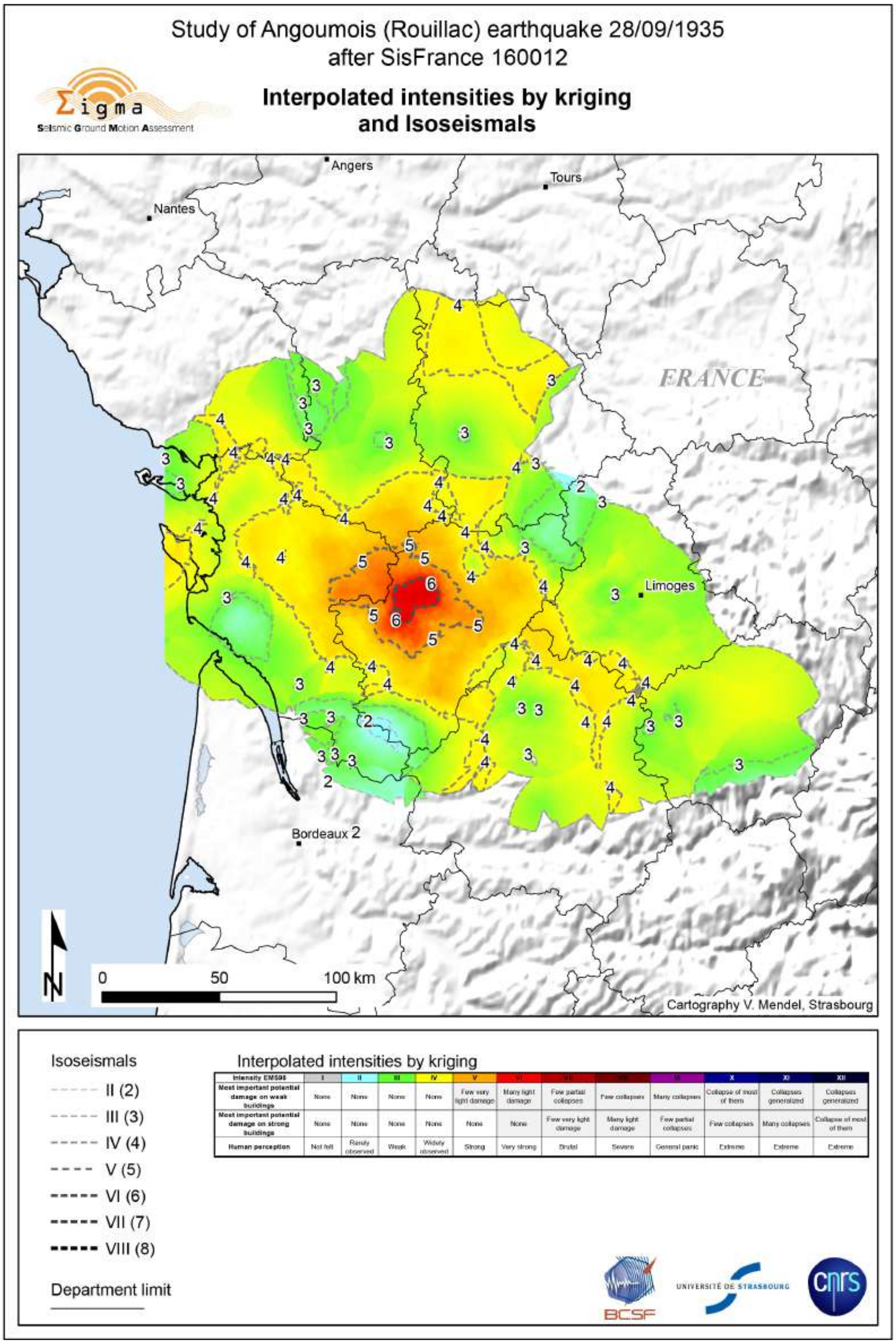
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

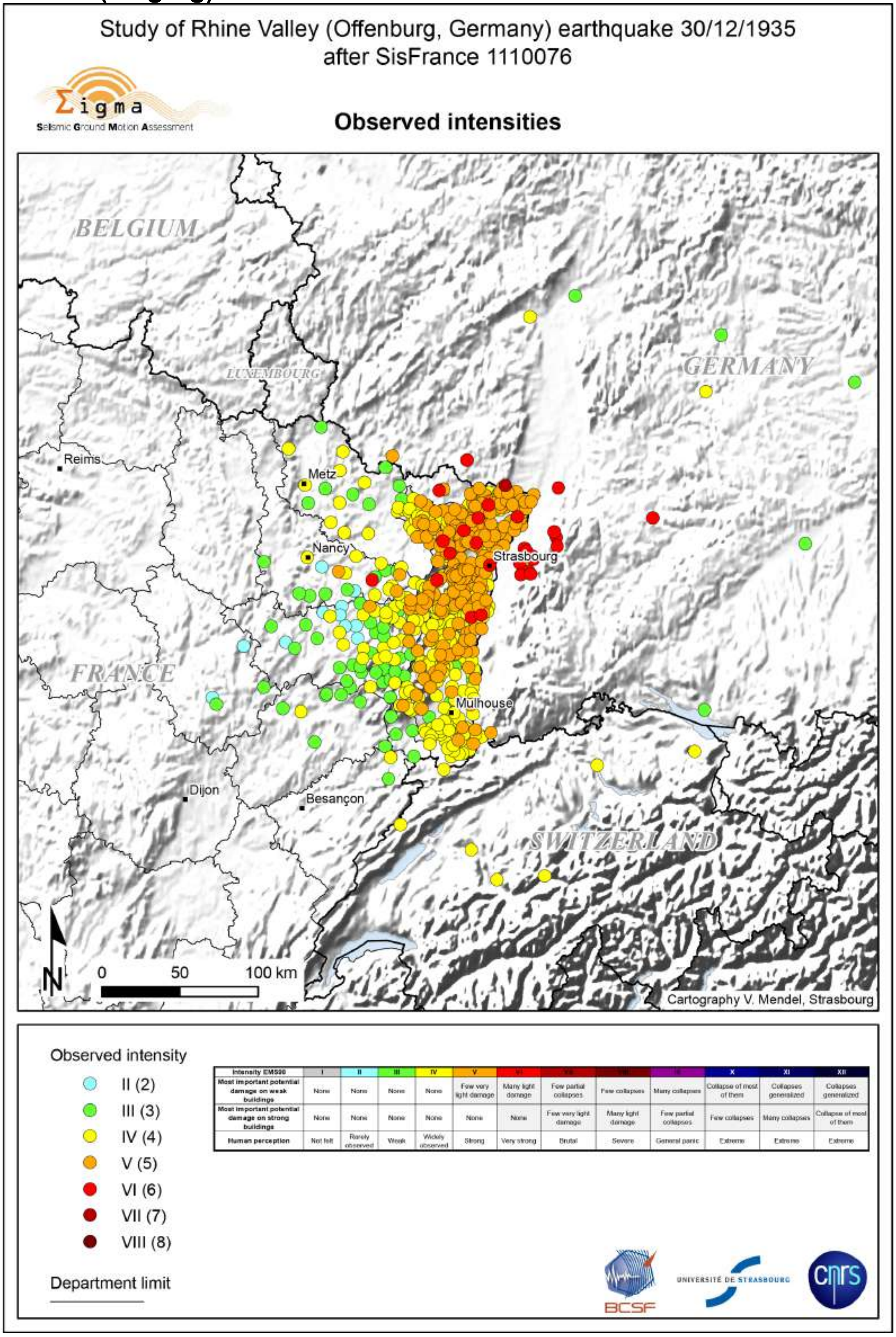


Study of Angoumois (Rouillac) earthquake 28/09/1935
after SisFrance 160012
Interpolated intensities by kriging
and observed intensities
Angers
Tours
Nantes
FRANCE
Limoges
Bordeaux
0
50
100 km
Cartography V. Mendel, Strasbourg
Observed intensity
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
Department limit
Interpolated intensities by kriging
Intensity EMS98
I
II
III
IV
V
X
XI
XII
Most important potential damage on weak buildings
Most important potential damage on strong buildings
Human perception
None
Few very light damage
Many light damage
Few partial collapses
Few collapses
Many collapses
Collapse of most of them
Collapses generalized
Not felt
Rarely observed
Weak
Widely observed
Strong
Very strong
Brutal
Severe
General panic
Extreme
UNIVERSITÉ DE STRASBOURG



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

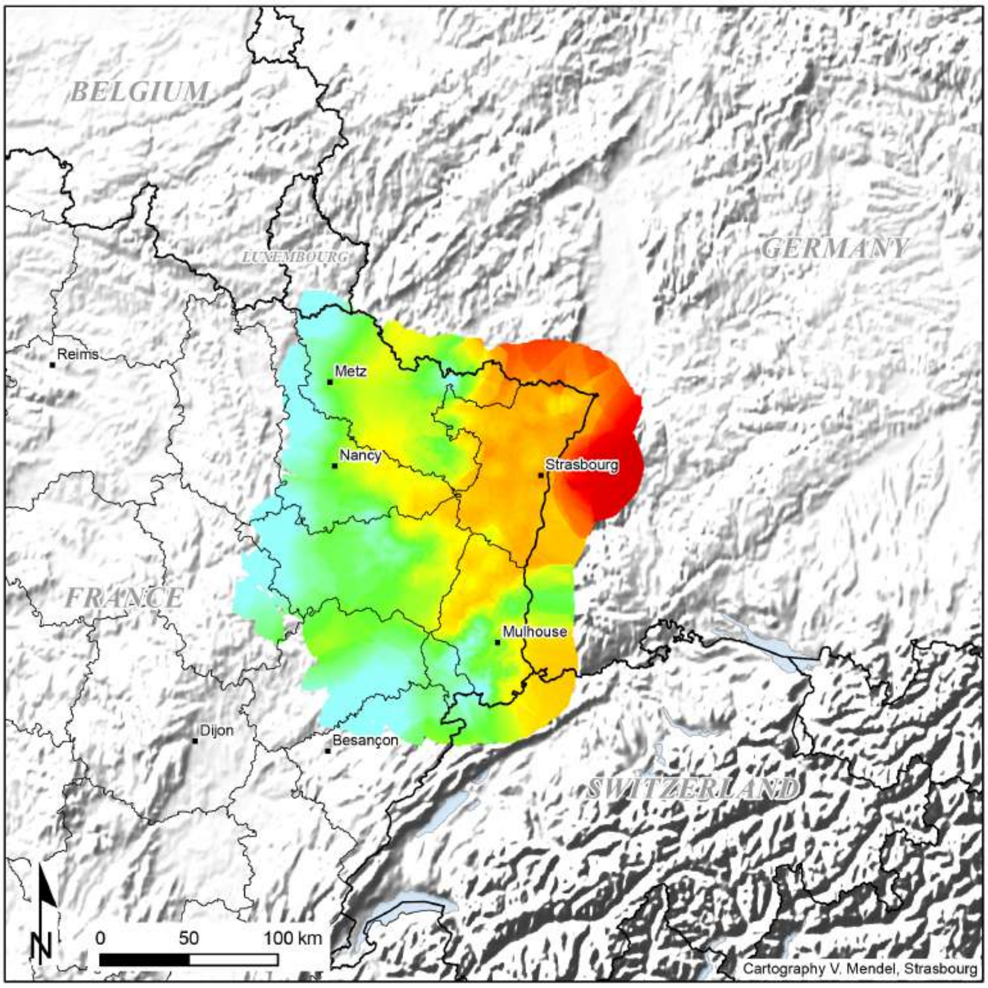
1935-12-30: Offenburg earthquake (Auto), Mw=4.6, Depth=30km, Isoseismal-min (Kriging)=none



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Rhine Valley (Offenburg, Germany) earthquake 30/12/1935
after SisFrance 1110076

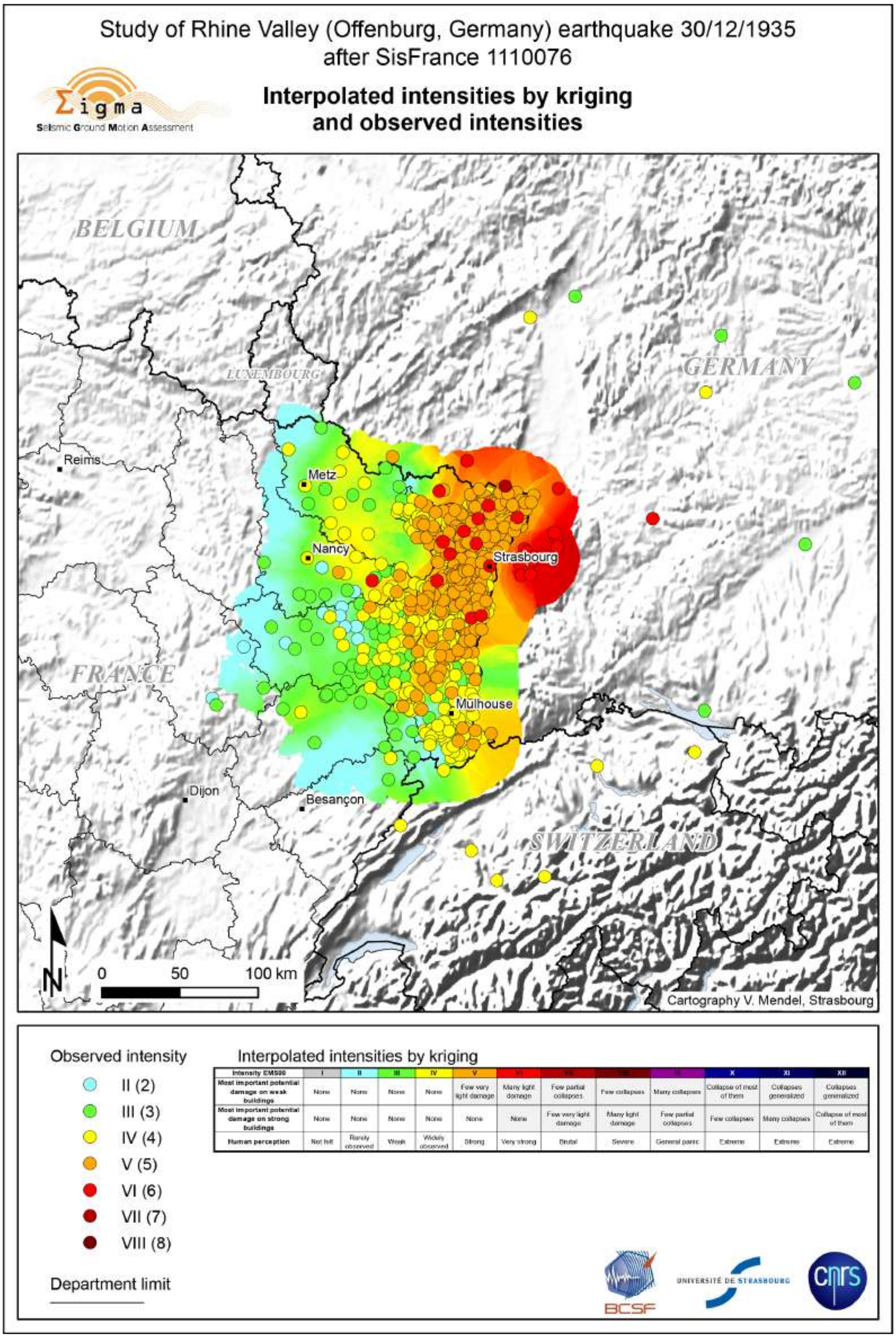
Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

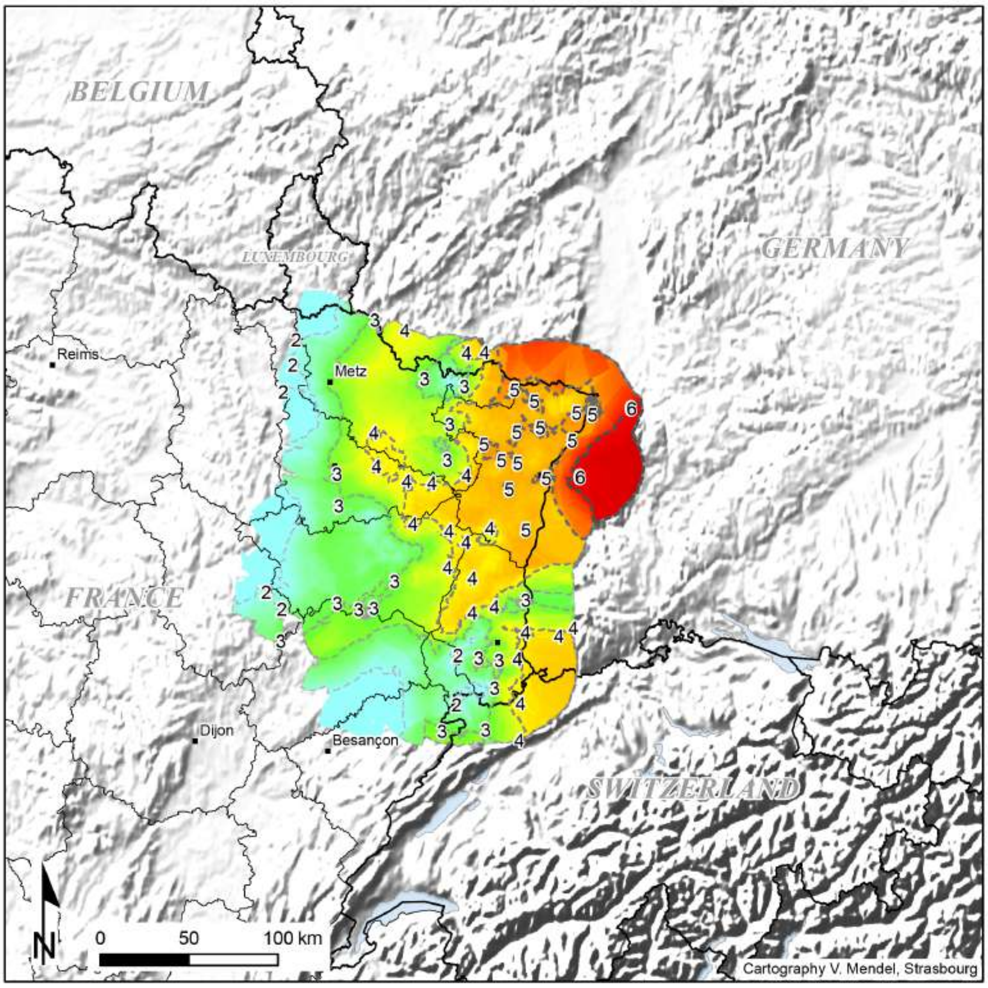
Department limit



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Rhine Valley (Offenburg, Germany) earthquake 30/12/1935
after SisFrance 1110076

Interpolated intensities by kriging and Isoseismals



Isoseismals

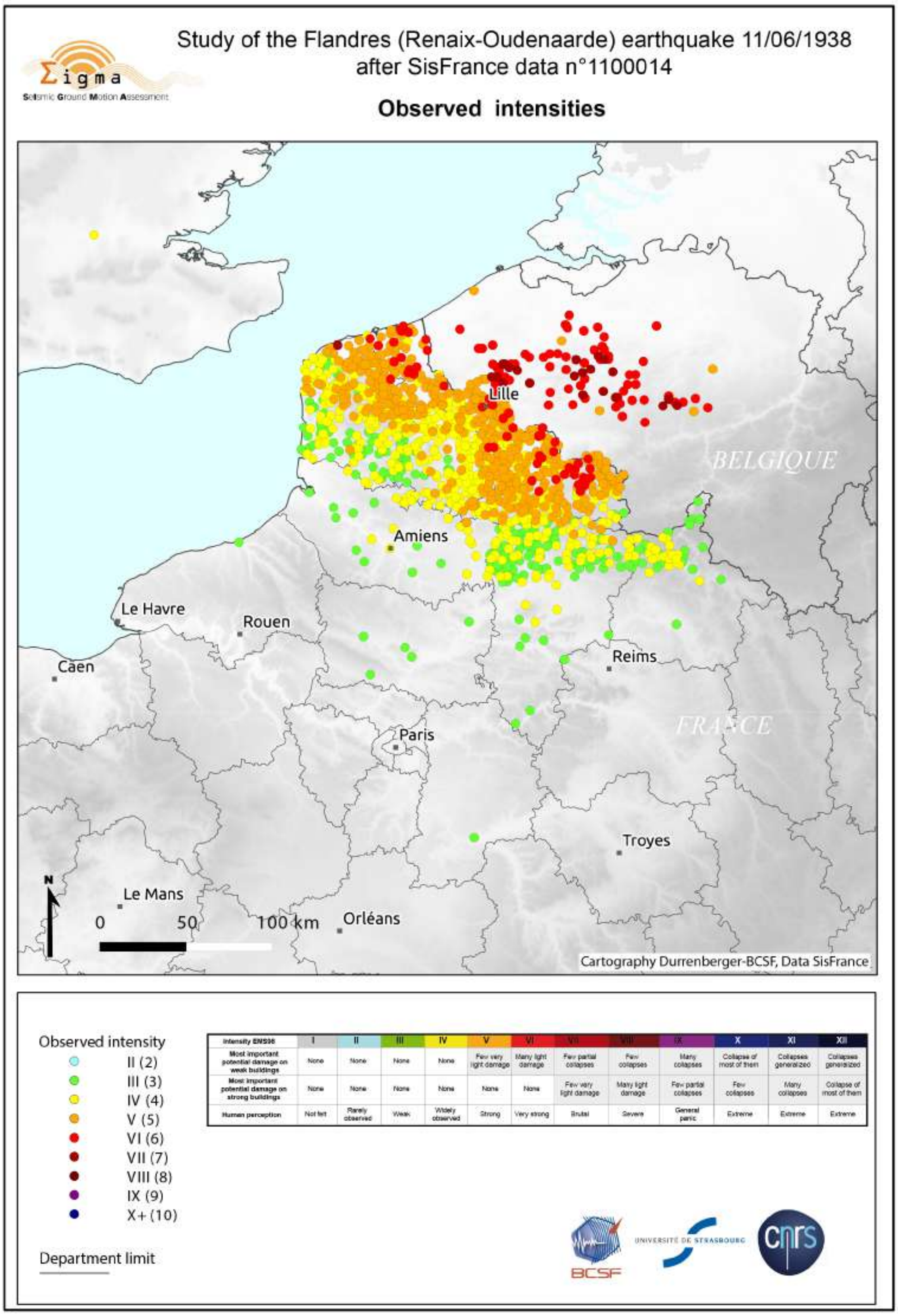
- II (2)
- III (3)
- IV (4)
- V (5)
- VI (6)
- VII (7)
- VIII (8)

Department limit

Interpolated intensities by kriging

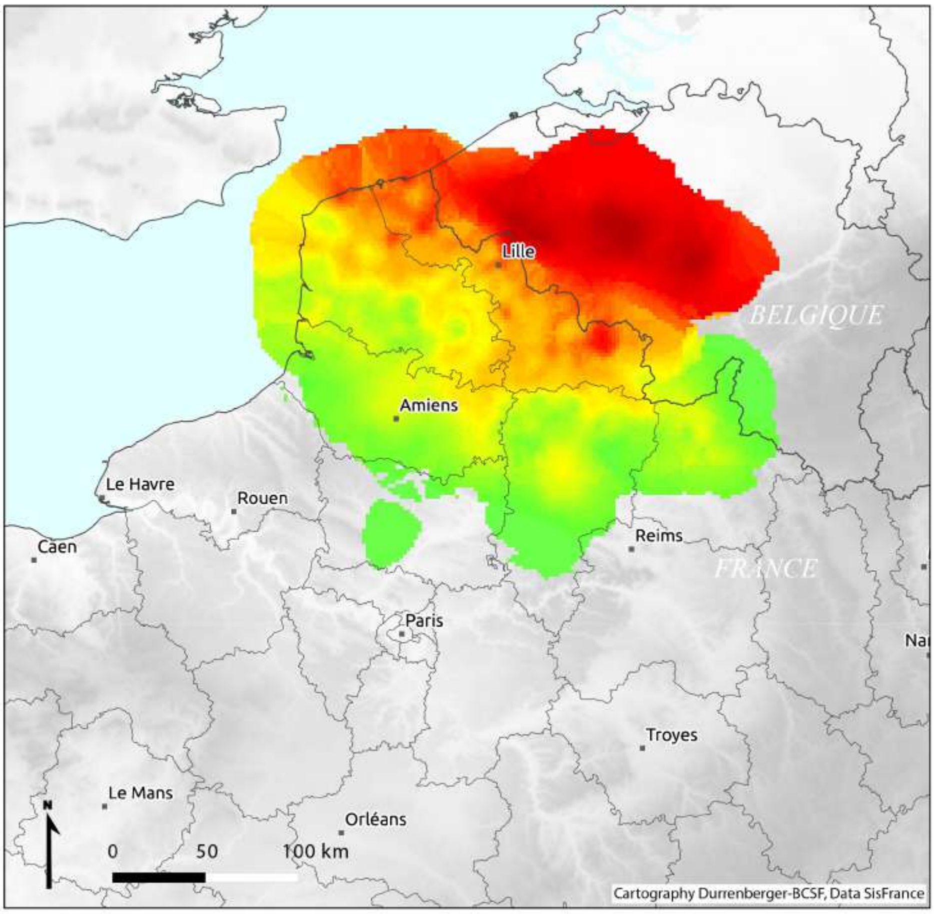
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1938-06-11: Flandres earthquake, Mw=5.1, Depth=30km, Isoseismal-min (Kriging)=6.0



Study of the Flandres (Renaix-Oudenaarde) earthquake 11/06/1938
after SisFrance data n°1100014

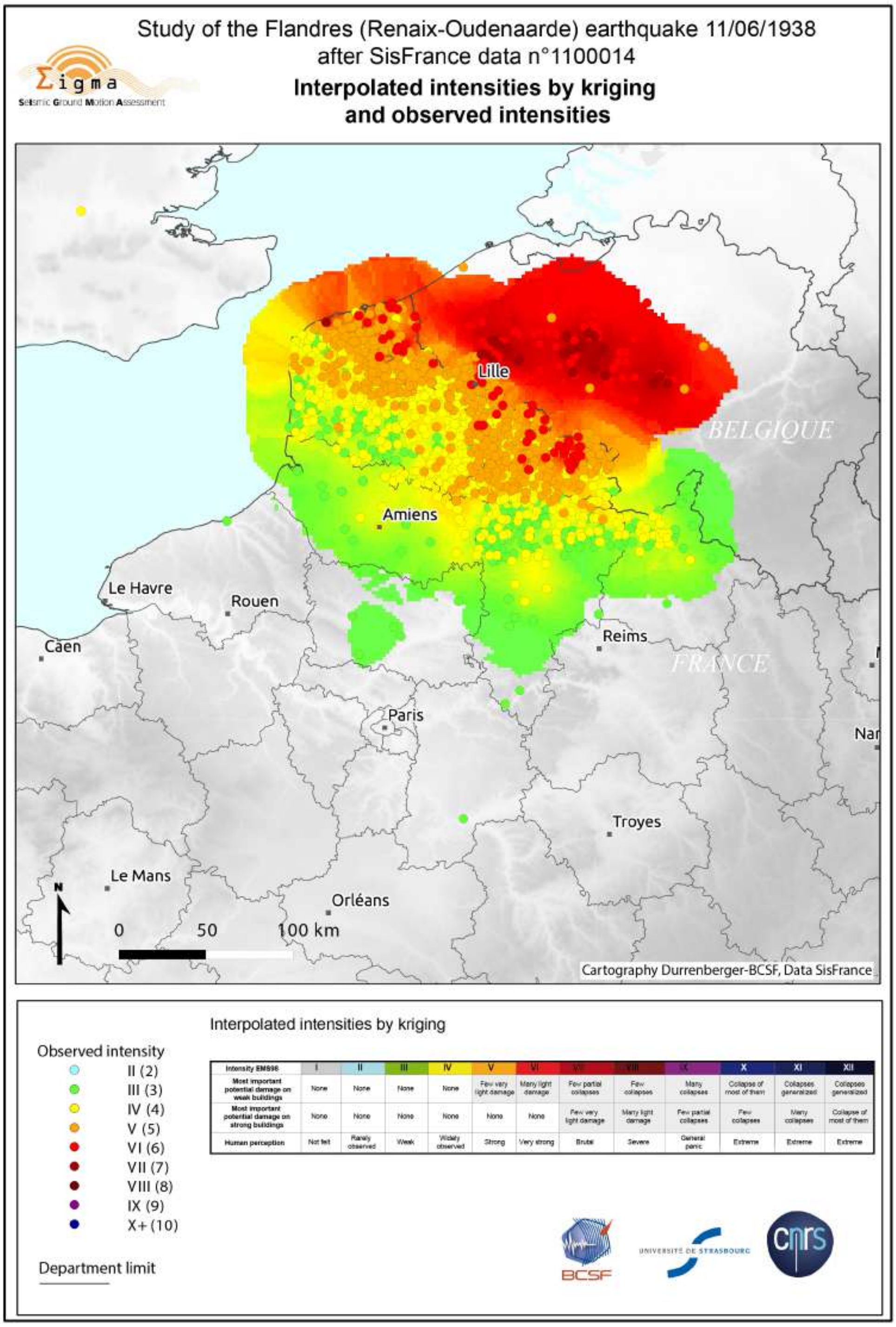
Interpolated intensities by kriging



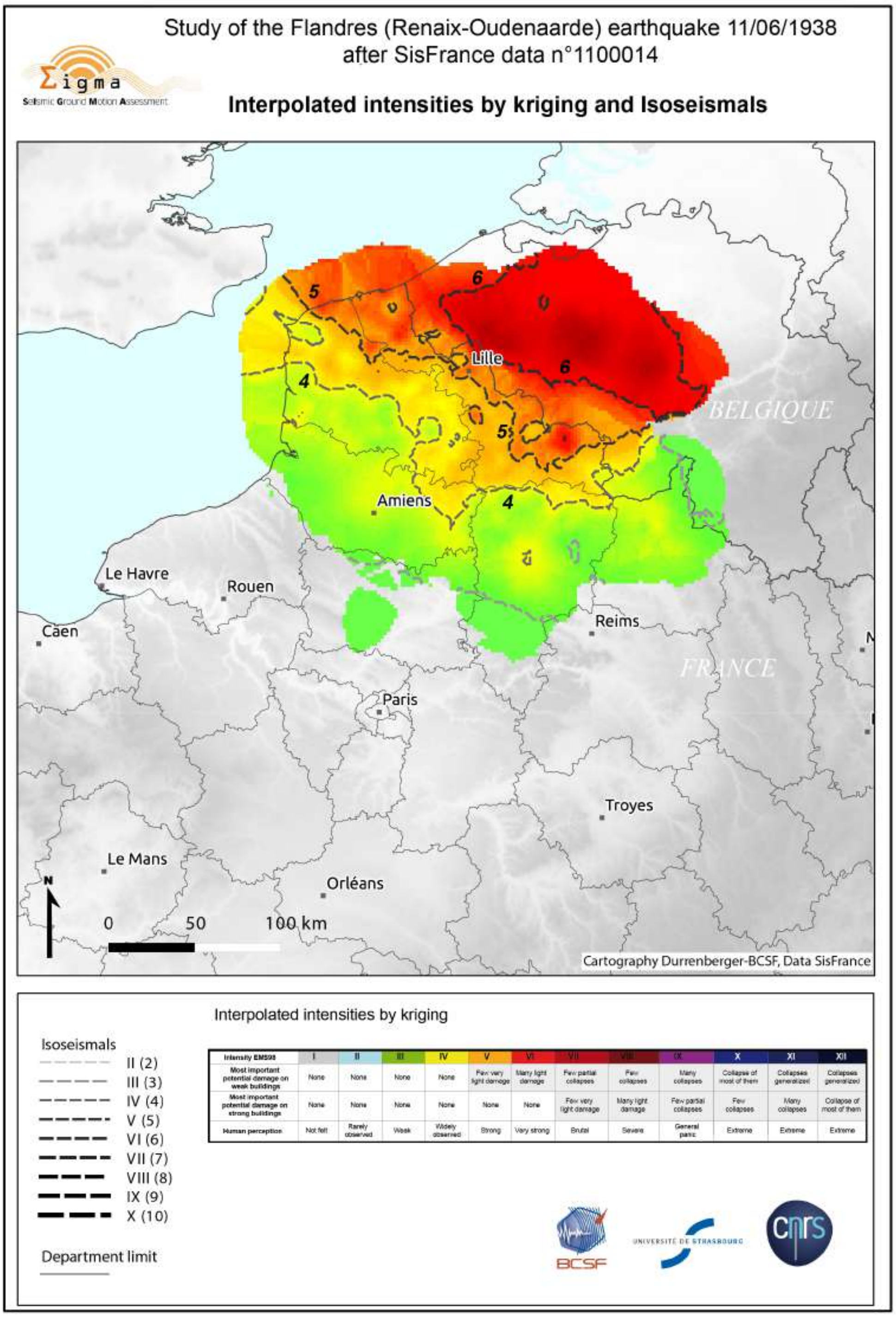
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

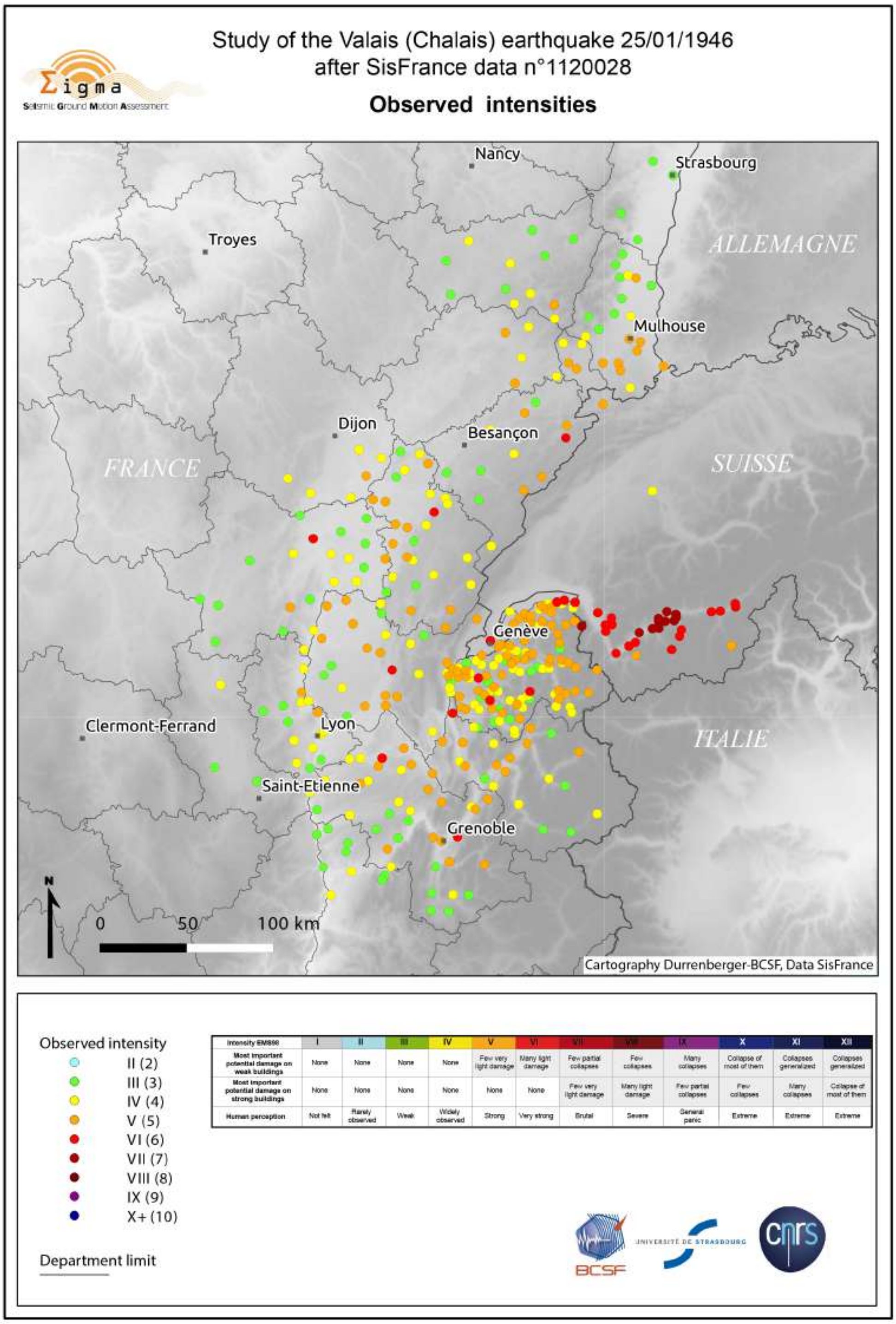


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

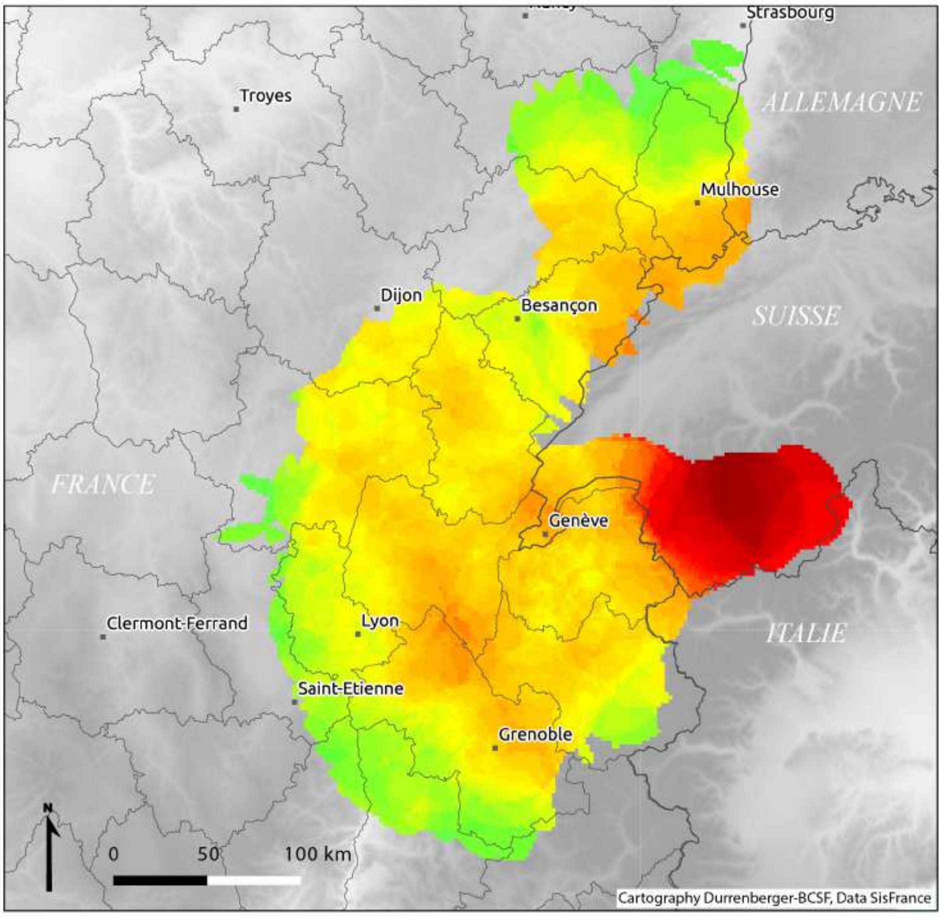
1946-01-25: Valais earthquake, Mw=5.8, Depth=5km, Isoseismal-min (Kriging)=none



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of the Valais (Chalais) earthquake 25/01/1946
after SisFrance data n°1120028

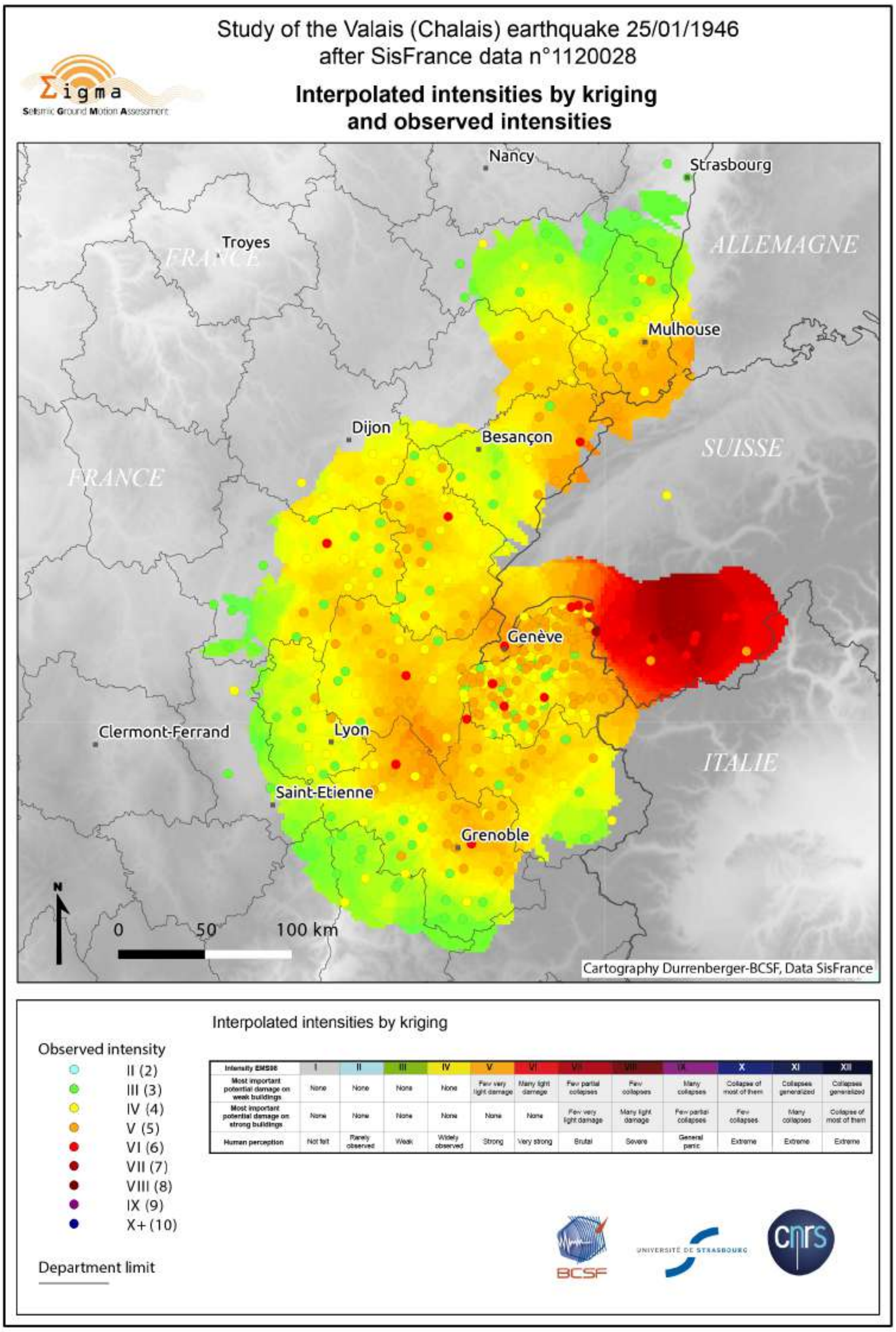
Interpolated intensities by kriging



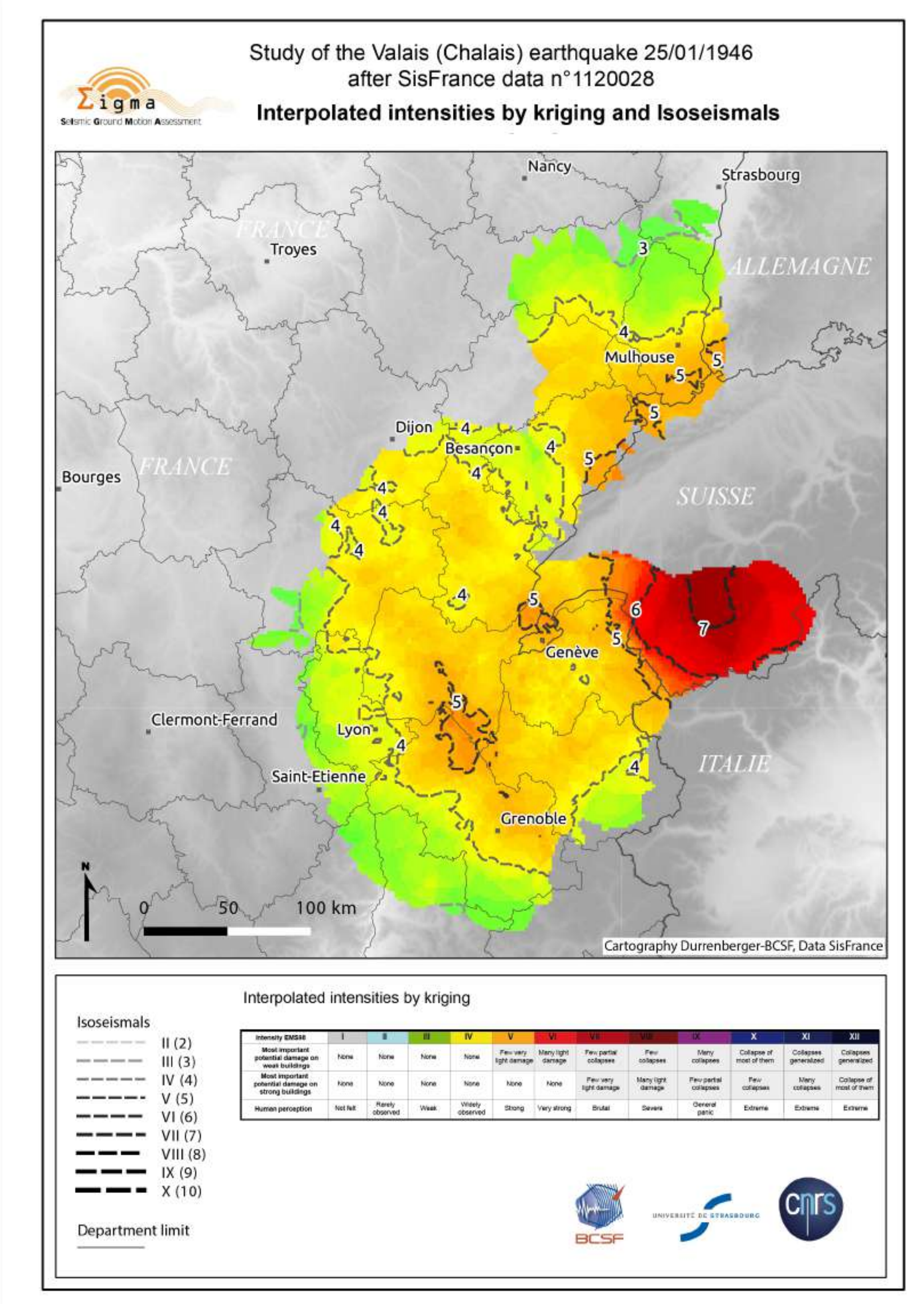
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

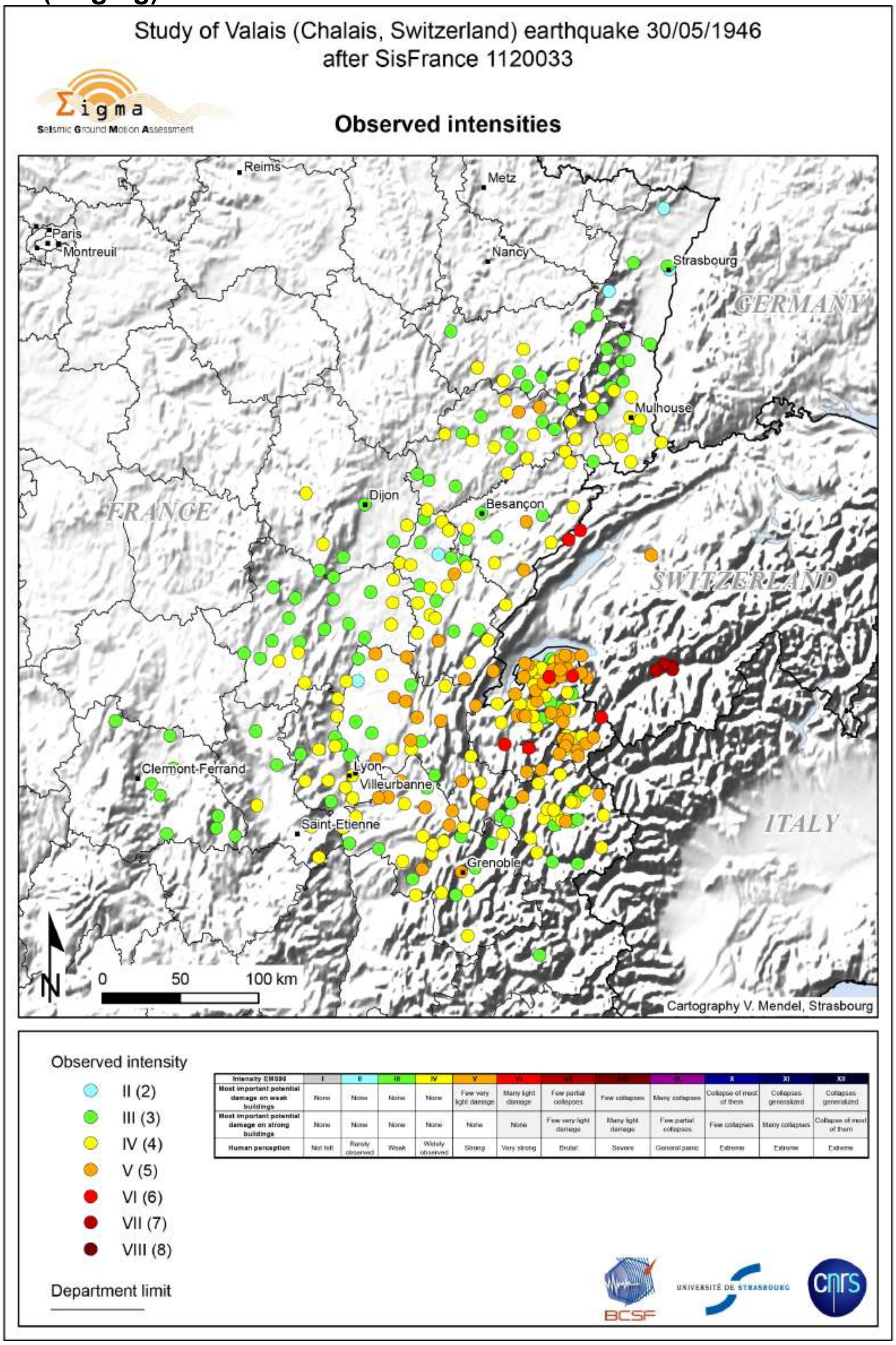


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

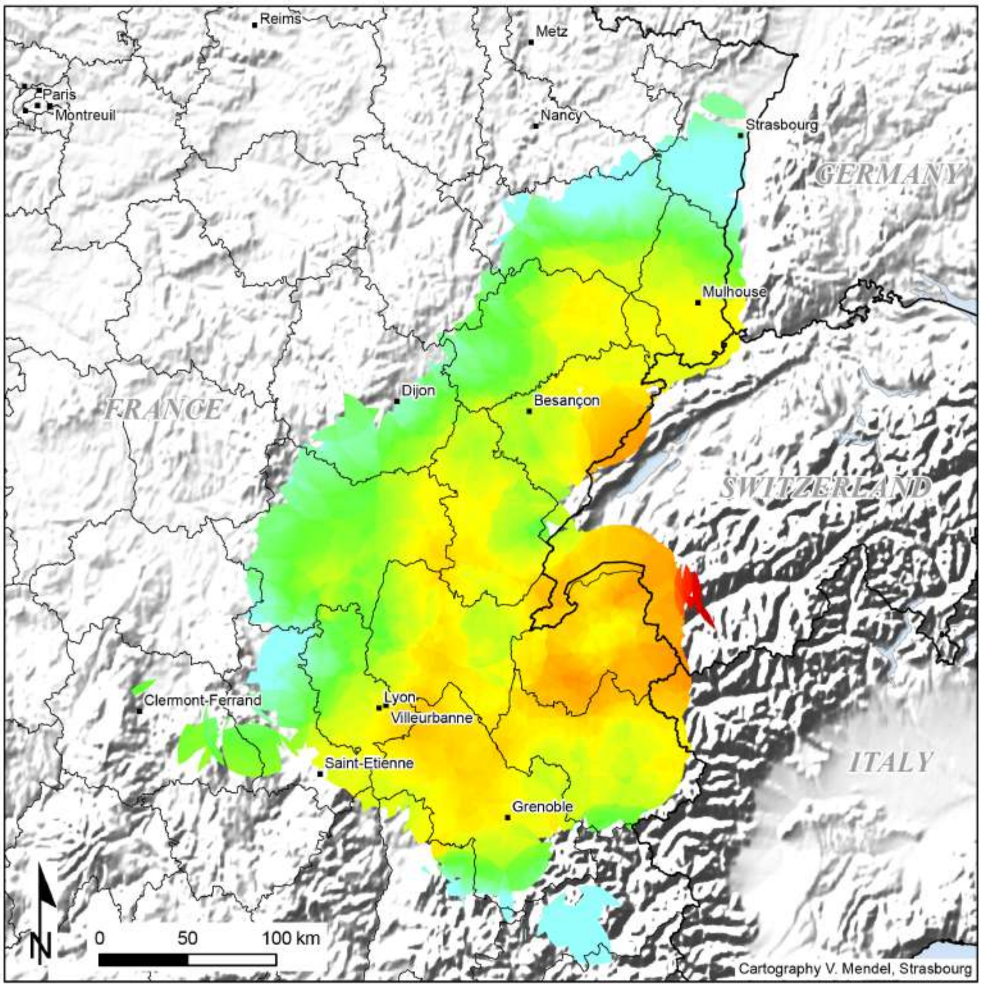
1946-05-30: Valais earthquake (Auto), Mw=5.5, Depth=unknown, Isoseismal-min (Kriging)=none



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Valais (Chalais, Switzerland) earthquake 30/05/1946
after SisFrance 1120033

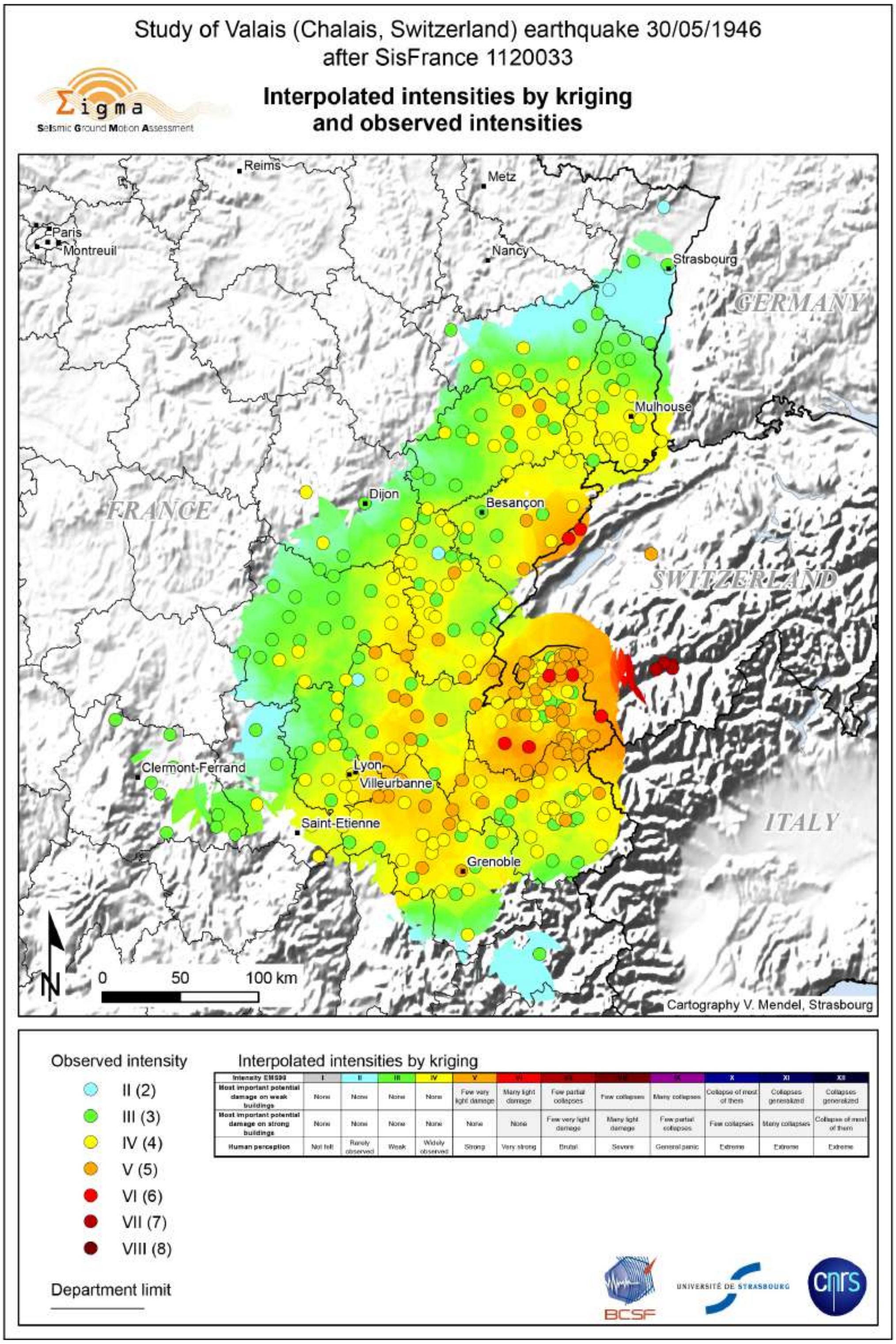
Interpolated intensities by kriging



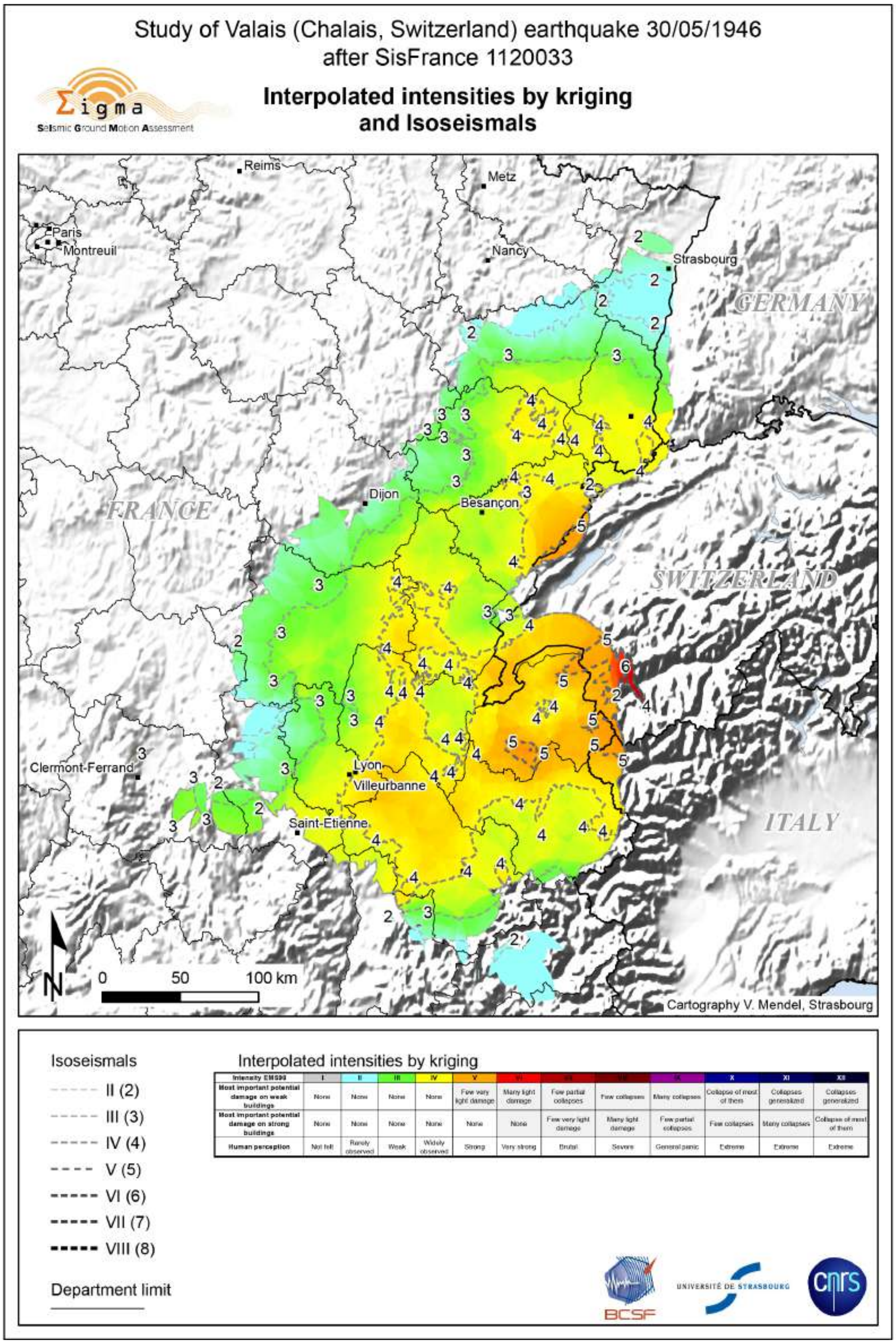
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

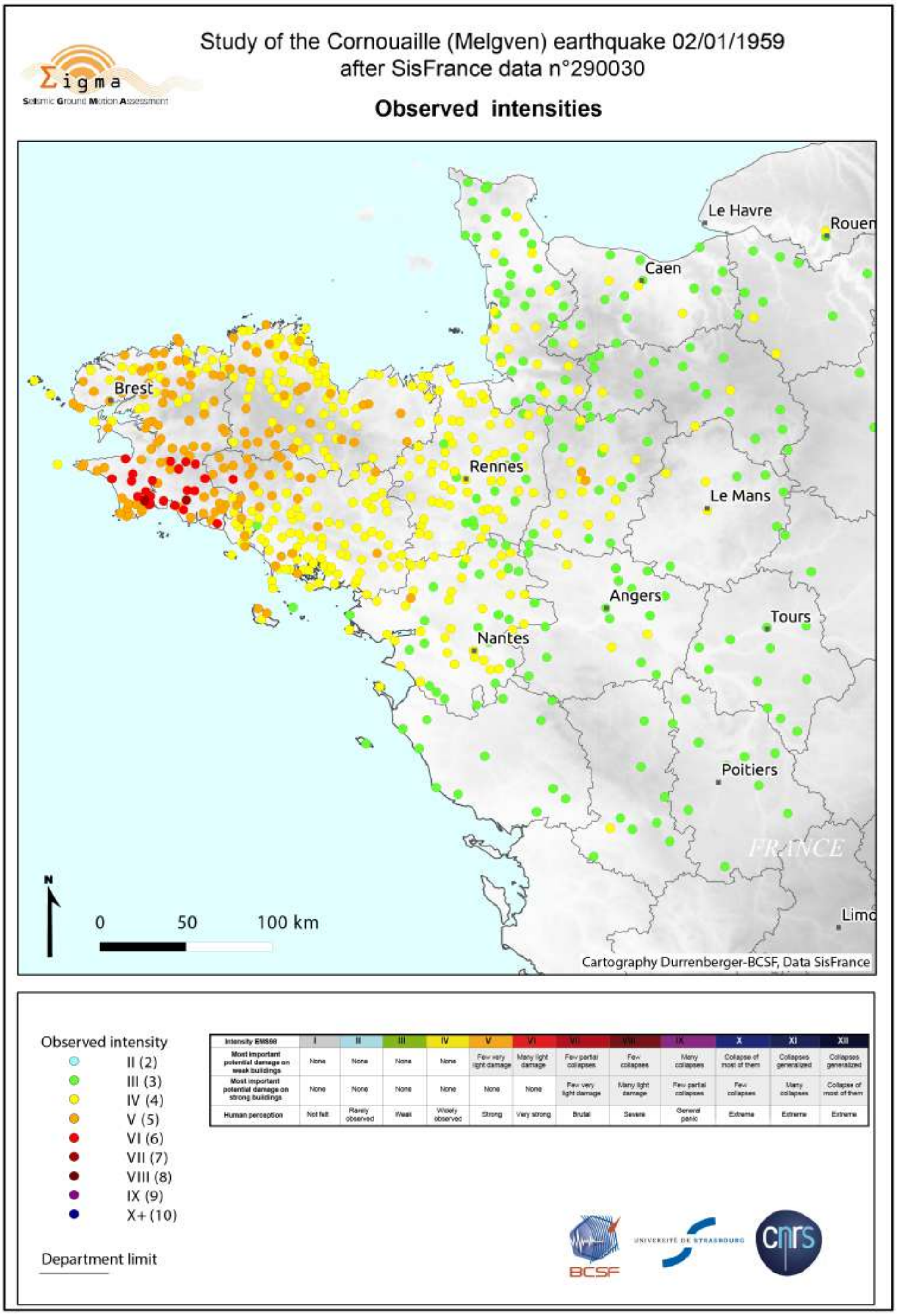


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



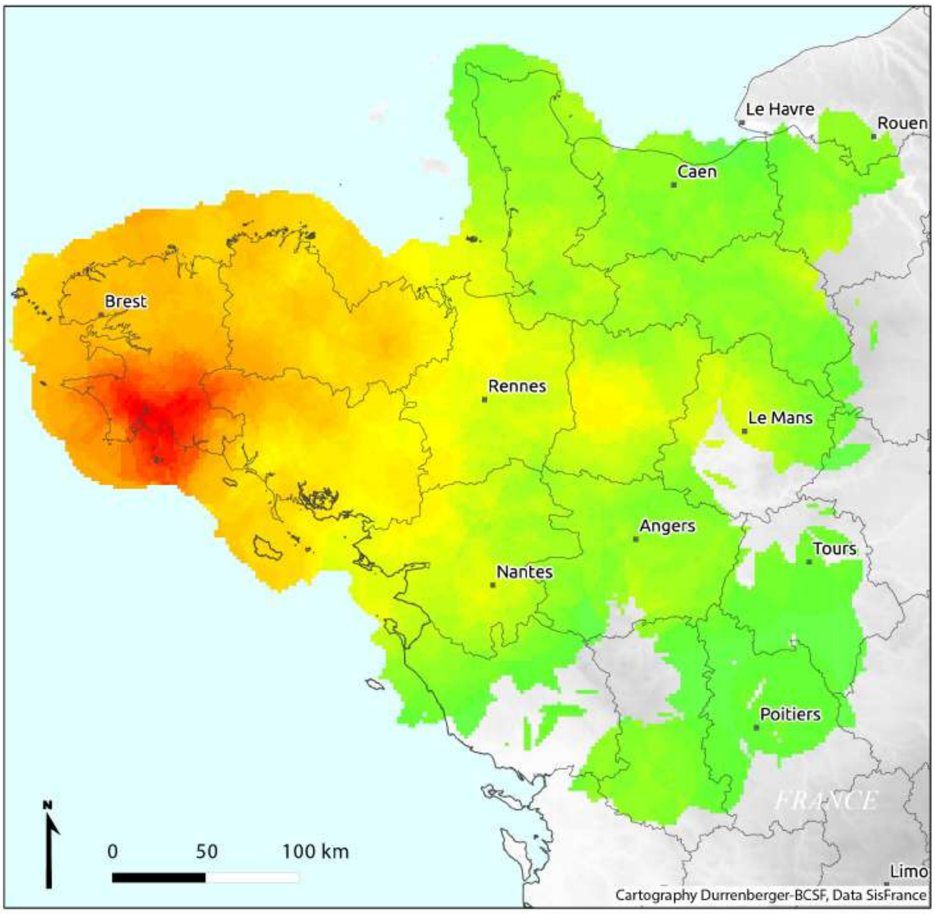
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1959-01-02: Cornouaille earthquake, Mw=5.3, Depth=5km, Isoseismal-min (Kriging)=5.0



Study of the Cornouaille (Melgven) earthquake 02/01/1959
after SisFrance data n°290030

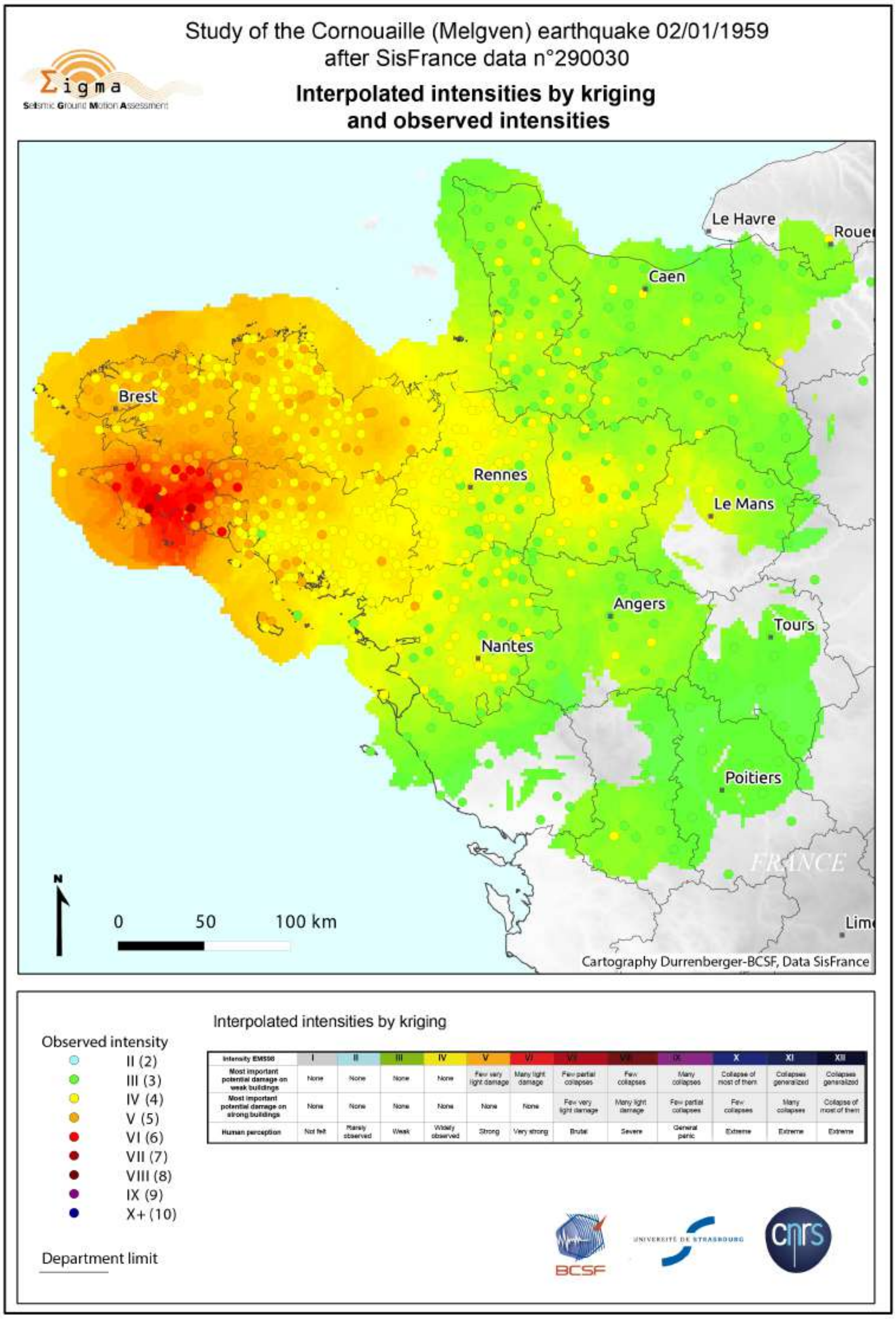
Interpolated intensities by kriging



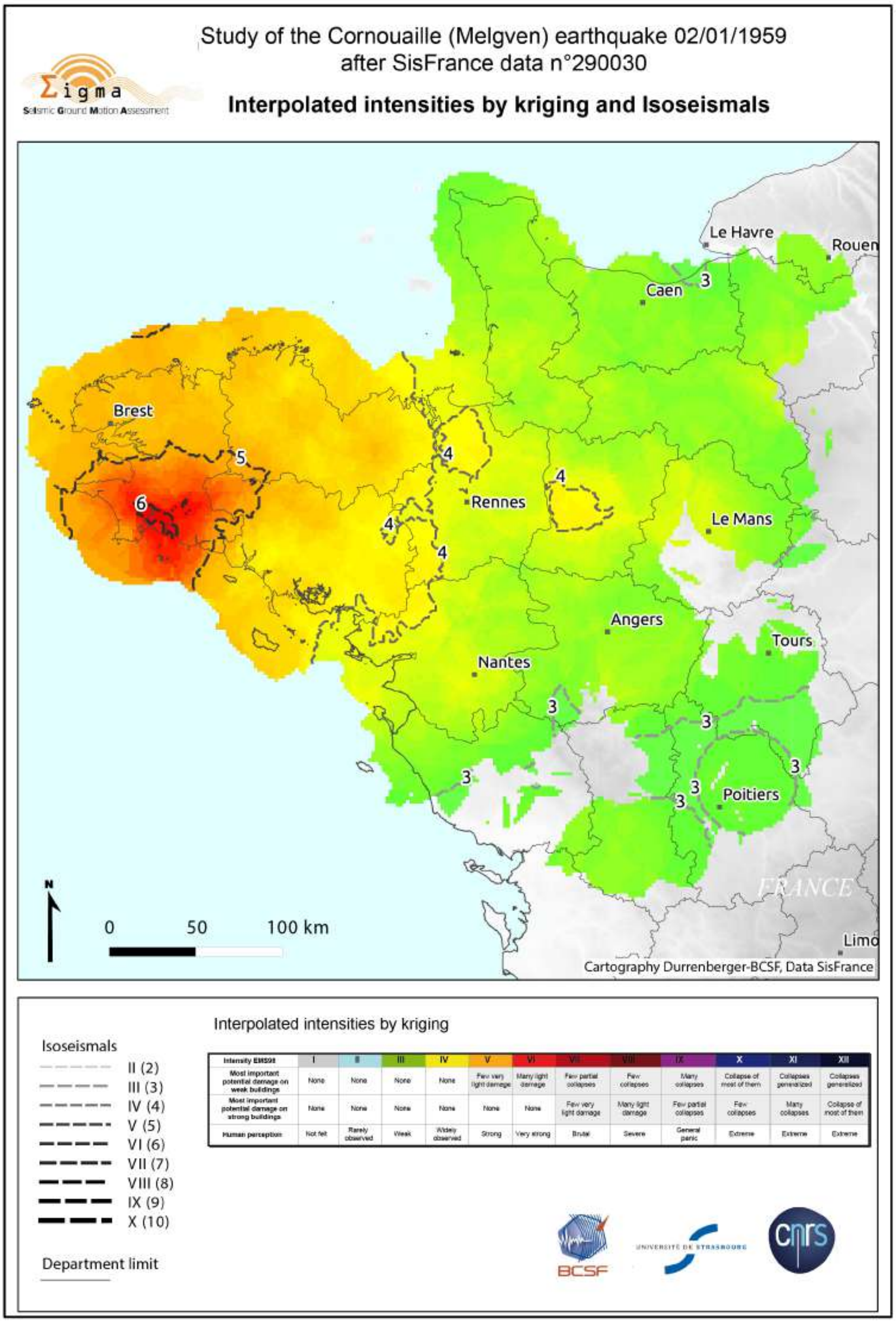
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

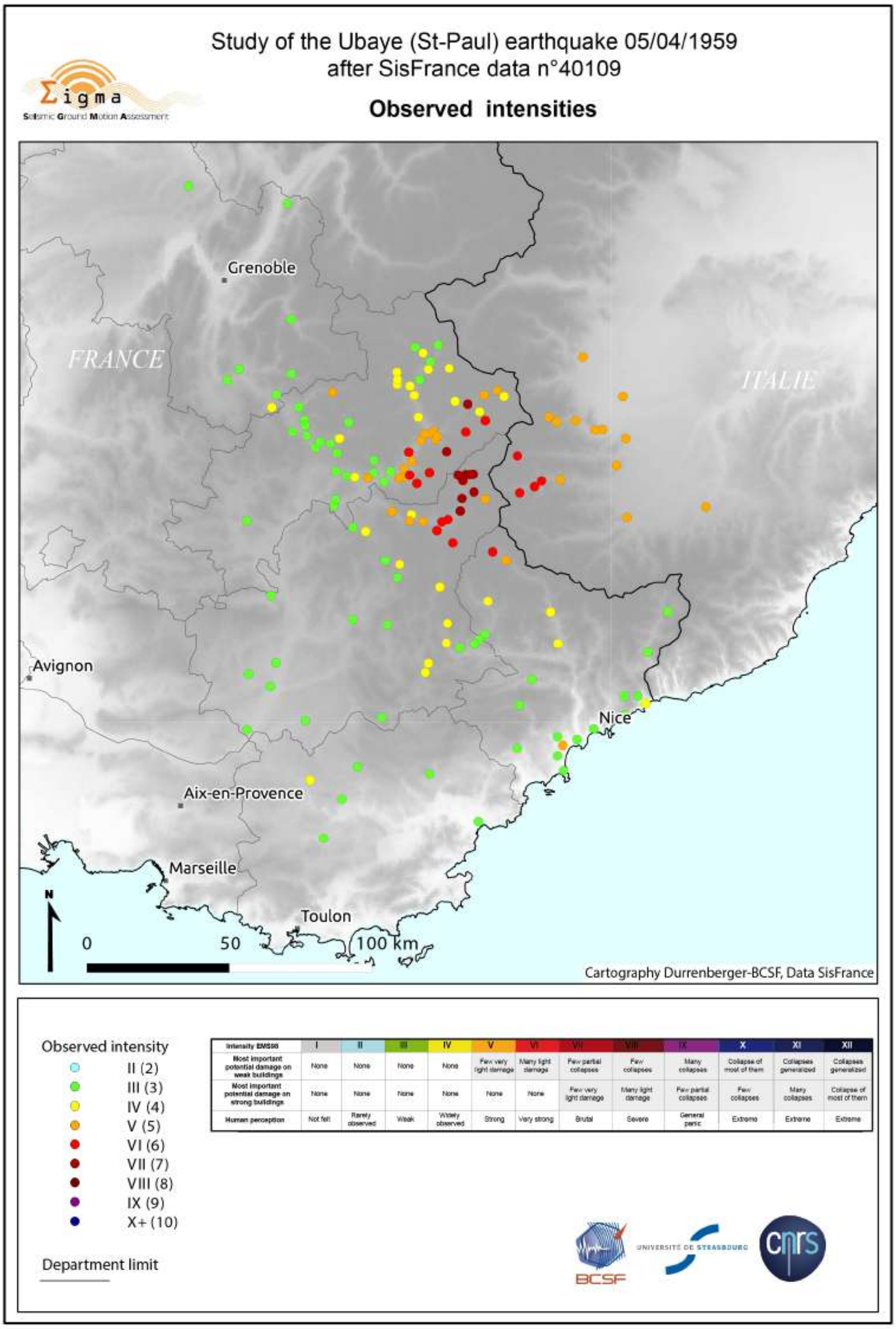


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



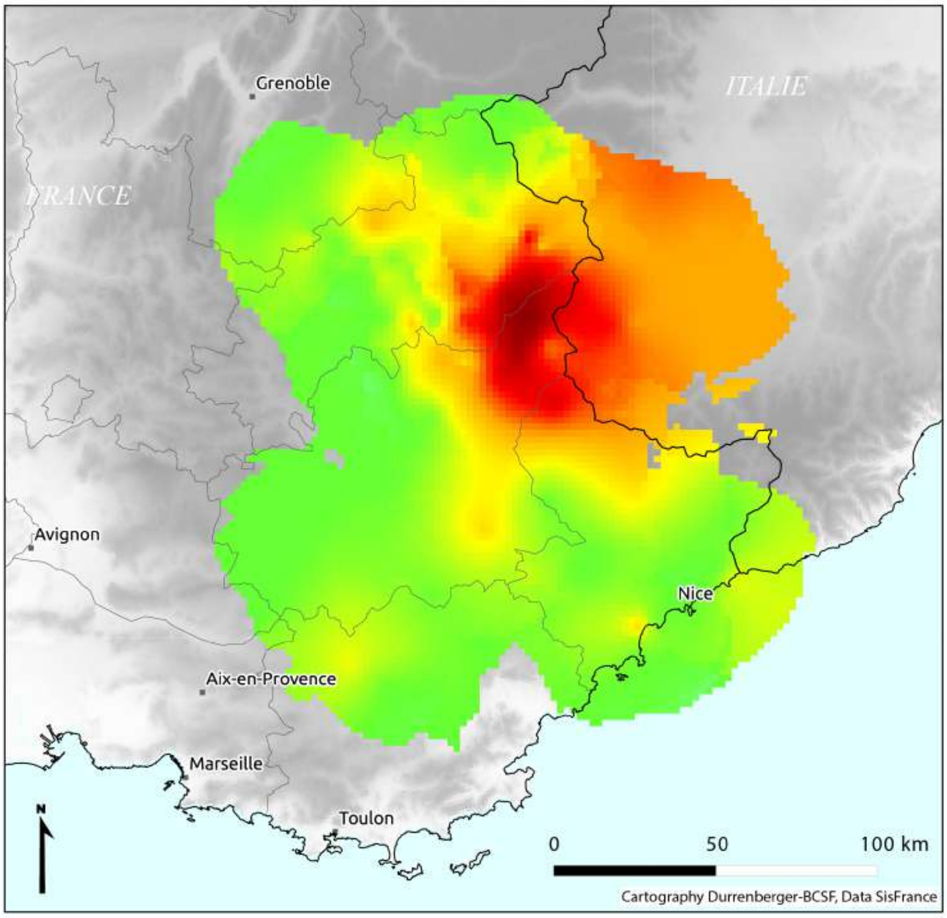
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1959-04-05: Ubaye earthquake, Mw=5.1, Depth=10km, Isoseismal-min (Kriging)=5.0



Study of the Ubaye (St-Paul) earthquake 05/04/1959
after SisFrance data n°40109

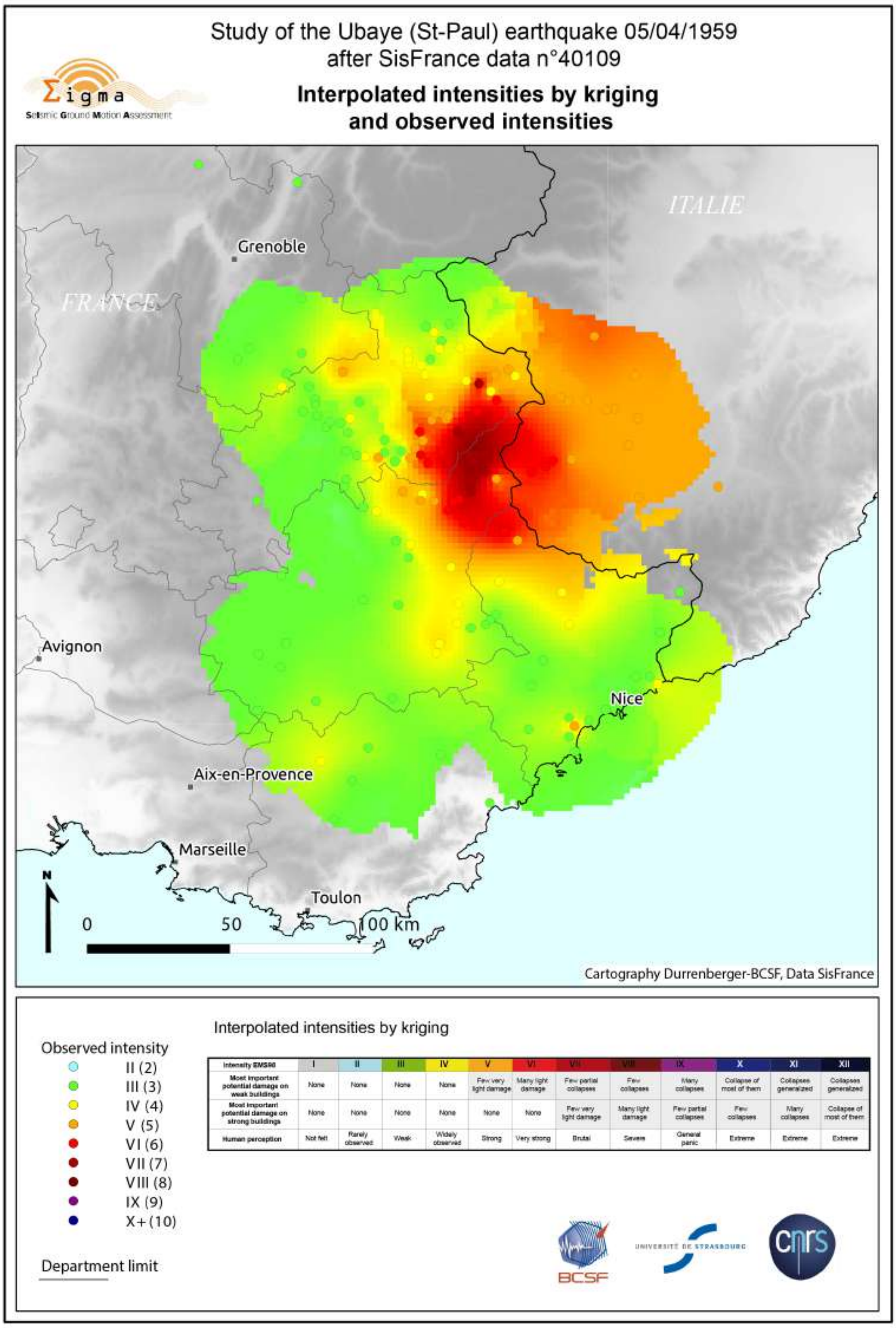
Interpolated intensities by kriging



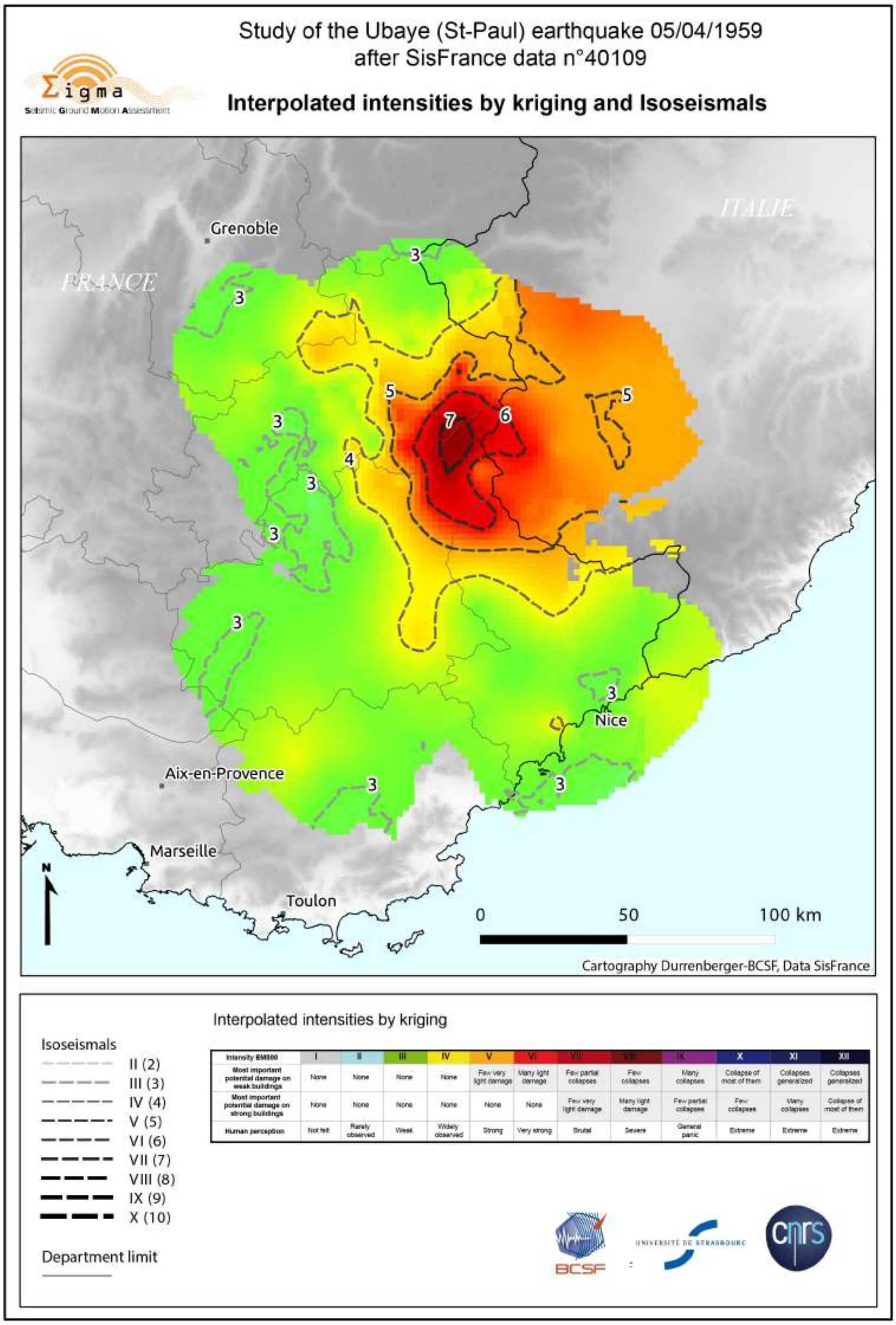
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

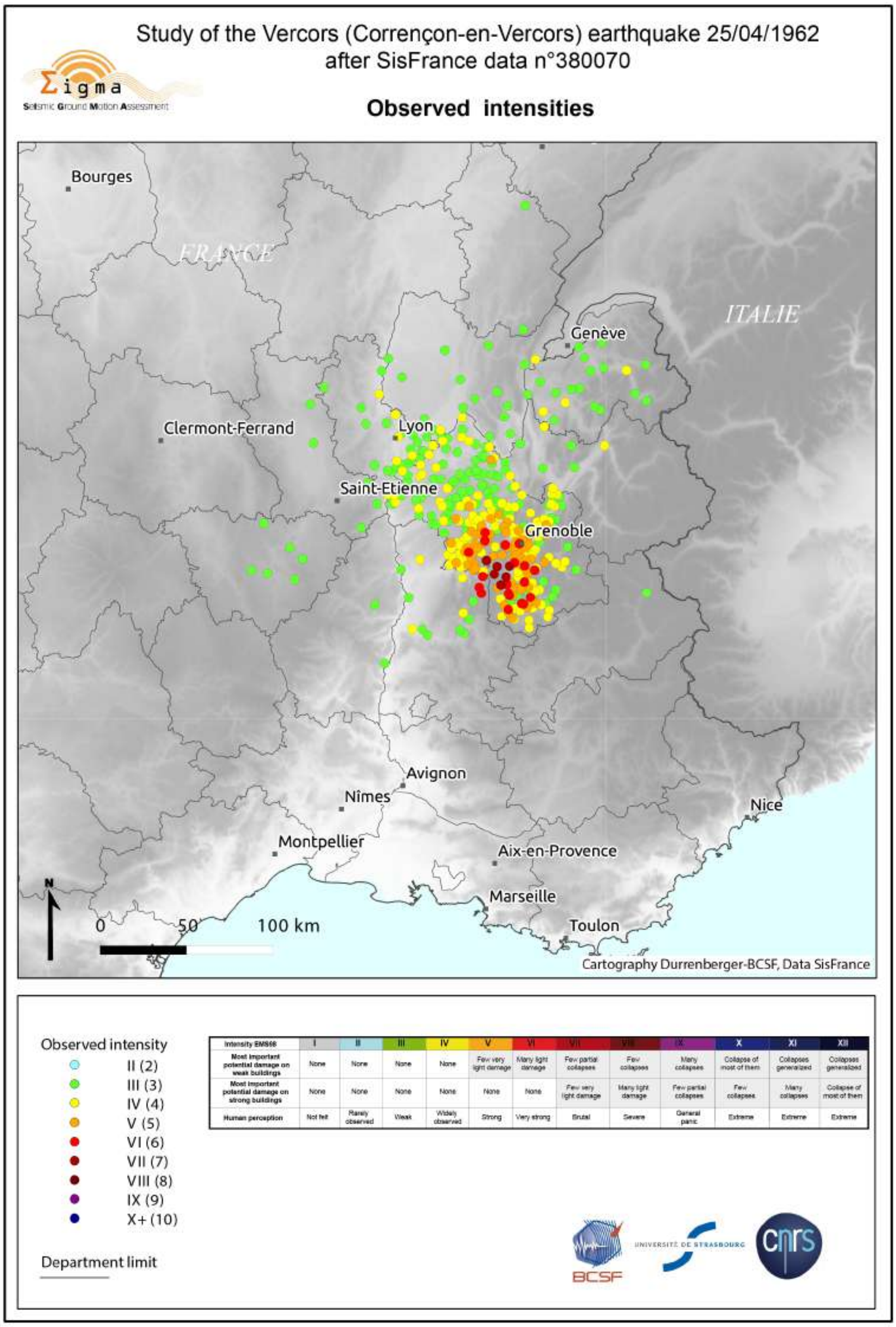


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

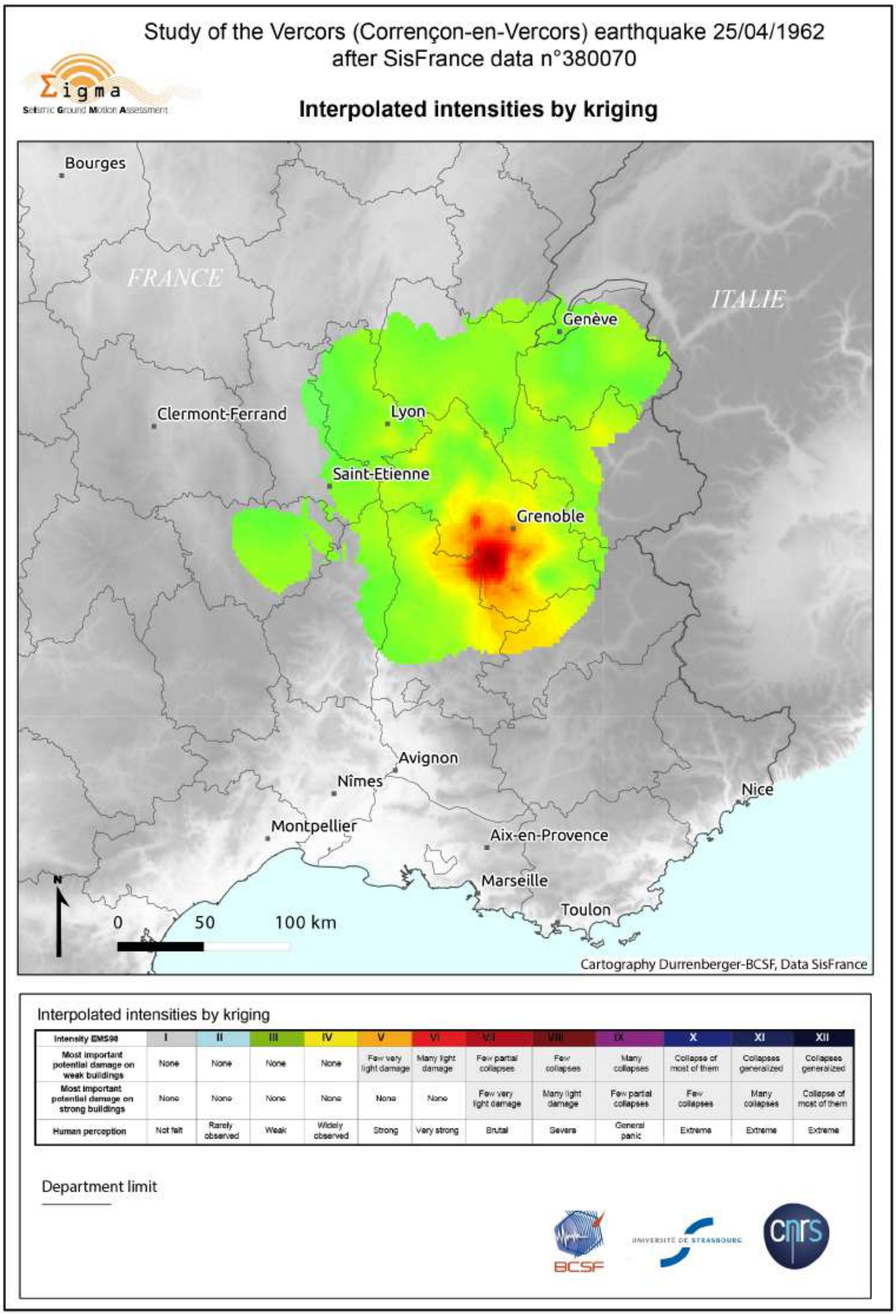


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

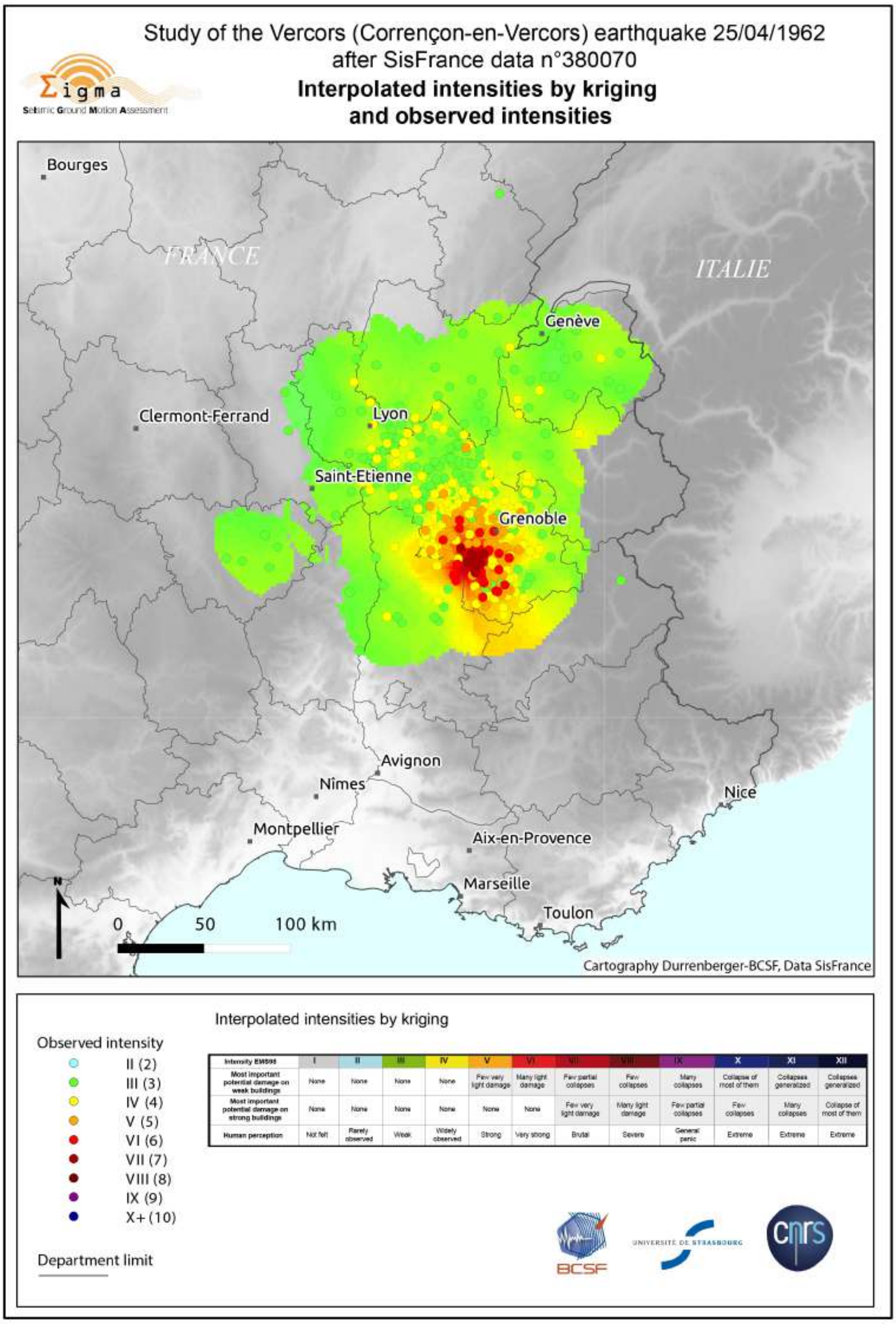
1962-04-25: Vercors earthquake, Mw=5.5, Depth=6km, Isoseismal-min (Kriging)=4.0



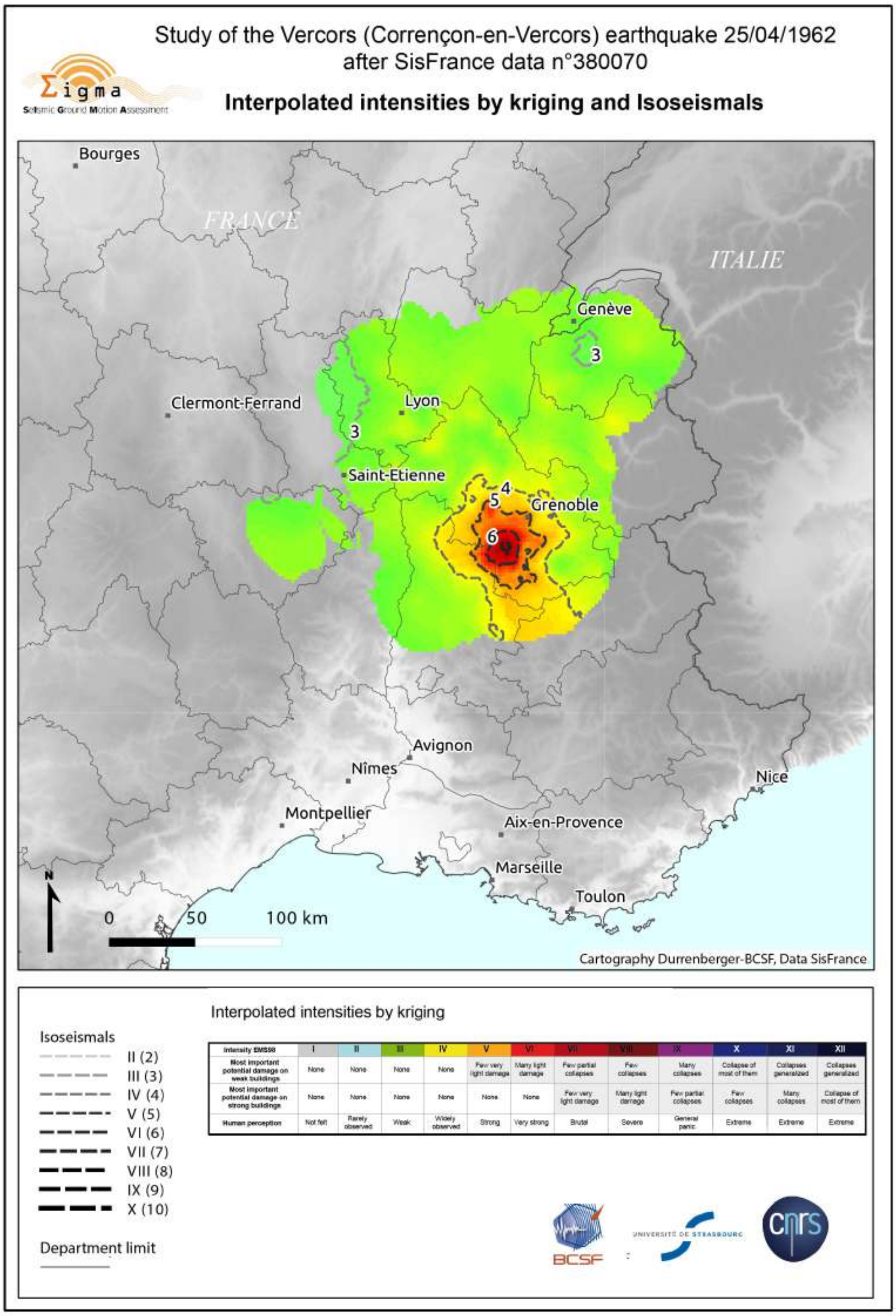
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme


Study of the Vercors (Corrençon-en-Vercors) earthquake 25/04/1962
after SisFrance data n°380070
Interpolated intensities by kriging and Isoseismals
Bourges
FRANCE
ITALIE
Genève
Clermont-Ferrand
Lyon
Saint-Etienne
Grenoble
Avignon
Nîmes
Nice
Montpellier
Aix-en-Provence
Marseille
Toulon
N
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Isoseismals
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98 | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII
Most important potential damage on weak buildings | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them | Collapses generalized | Collapses generalized
Most important potential damage on strong buildings | None | None | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them
Human perception | Not felt | Rarely observed | Weak | Widely observed | Strong | Very strong | Brutal | Severe | General panic | Extreme | Extreme | Extreme
BCSF
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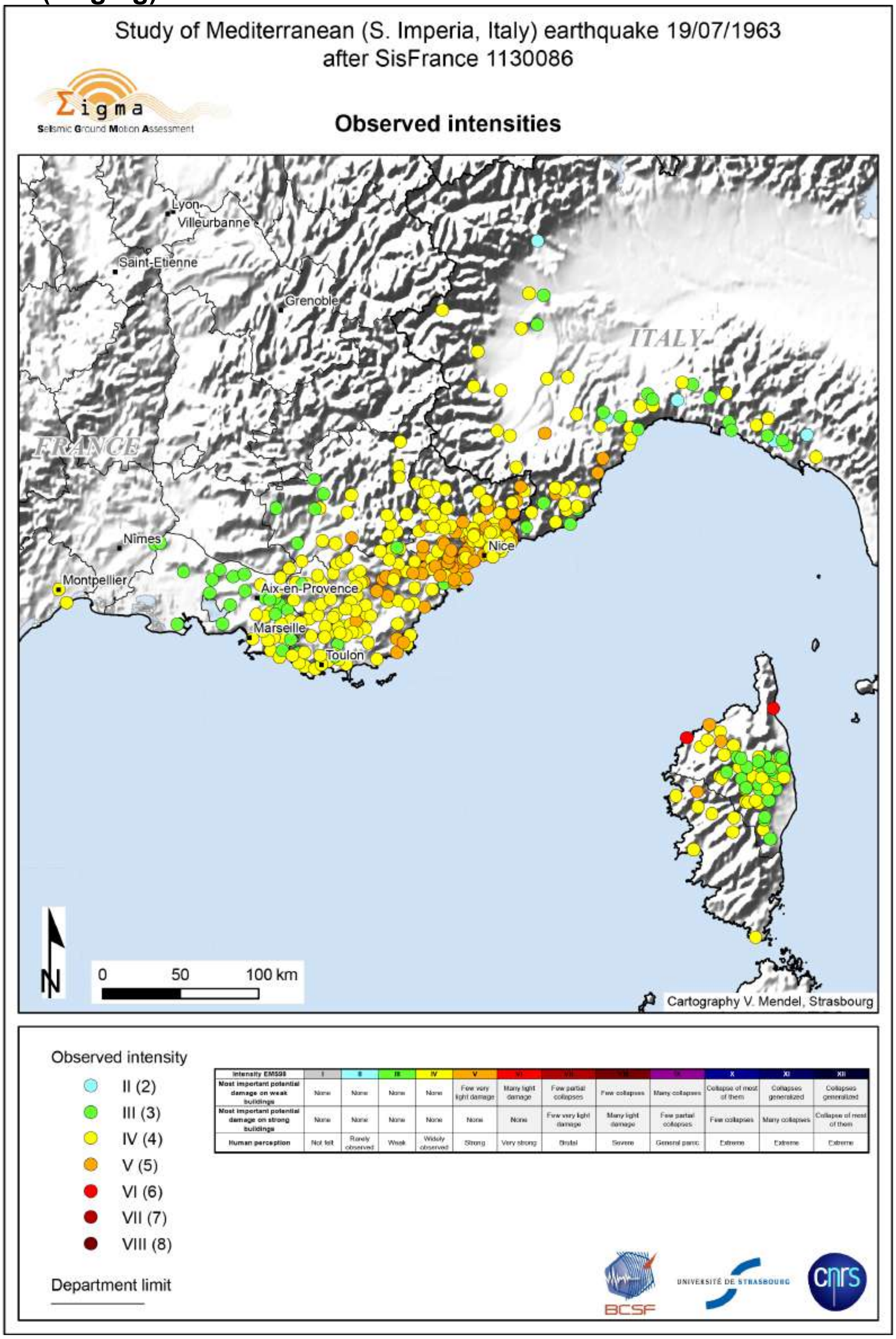
cnrs

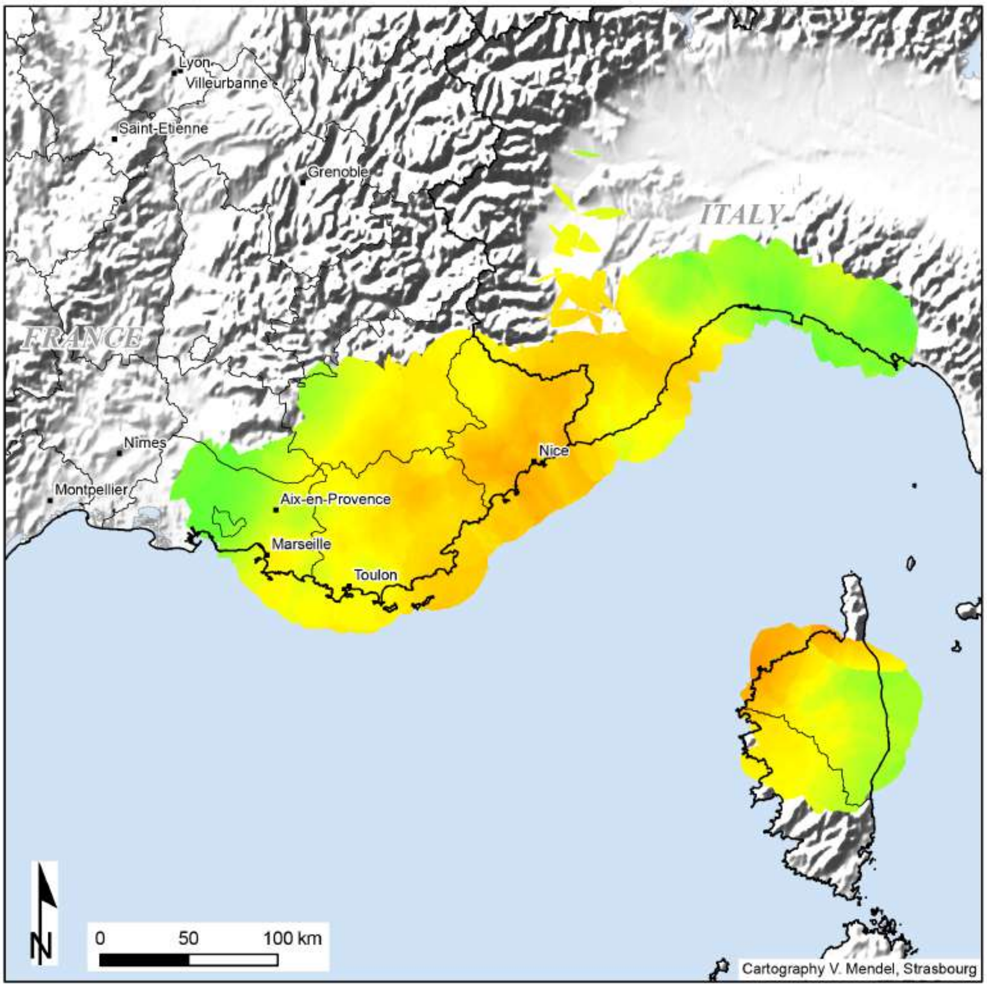
1963-07-19: Imperia earthquake (Auto), Mw=6.1, Depth=6km, Isoseismal-min (Kriging)=none



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Mediterranean (S. Imperia, Italy) earthquake 19/07/1963
after SisFrance 1130086

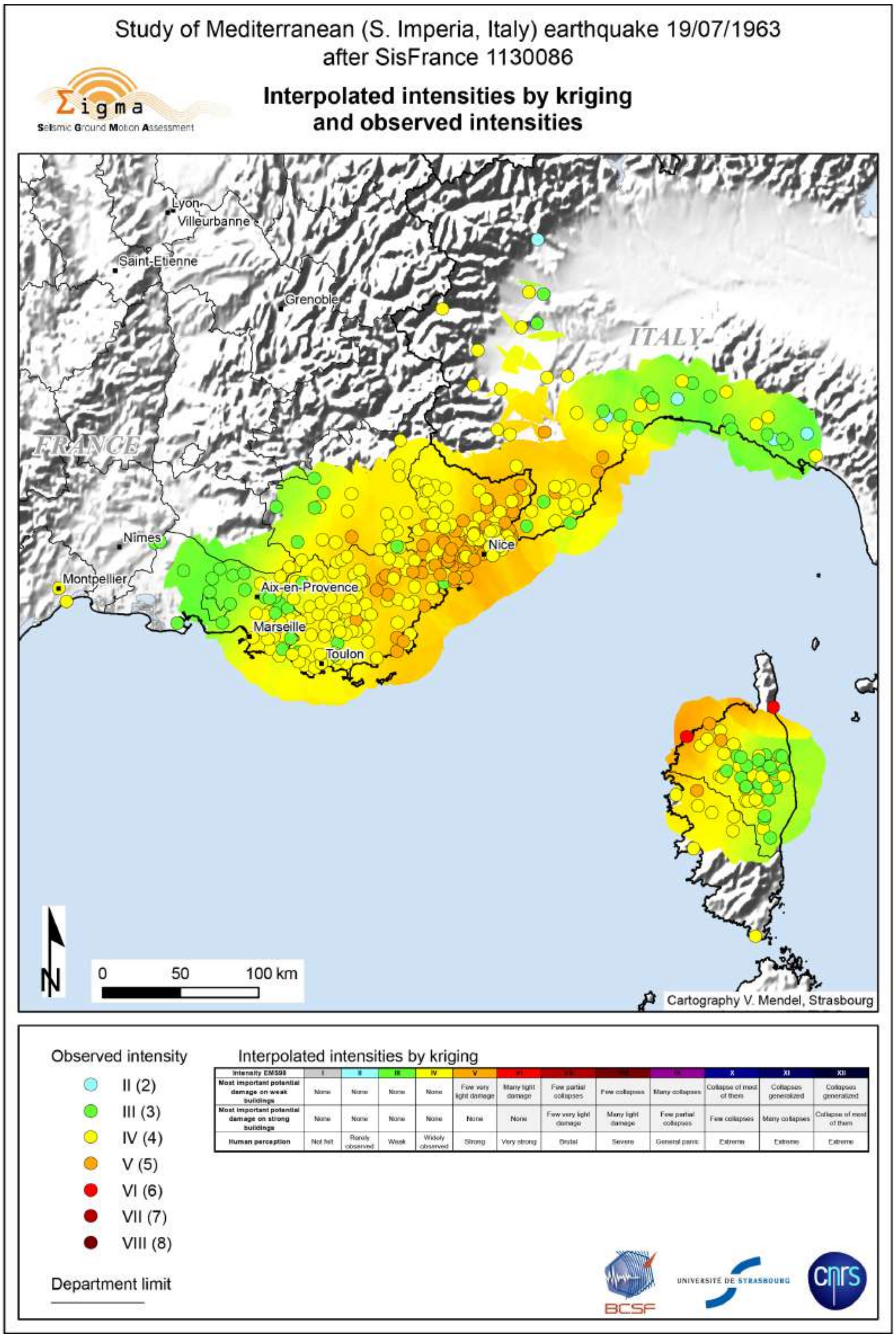
Interpolated intensities by kriging



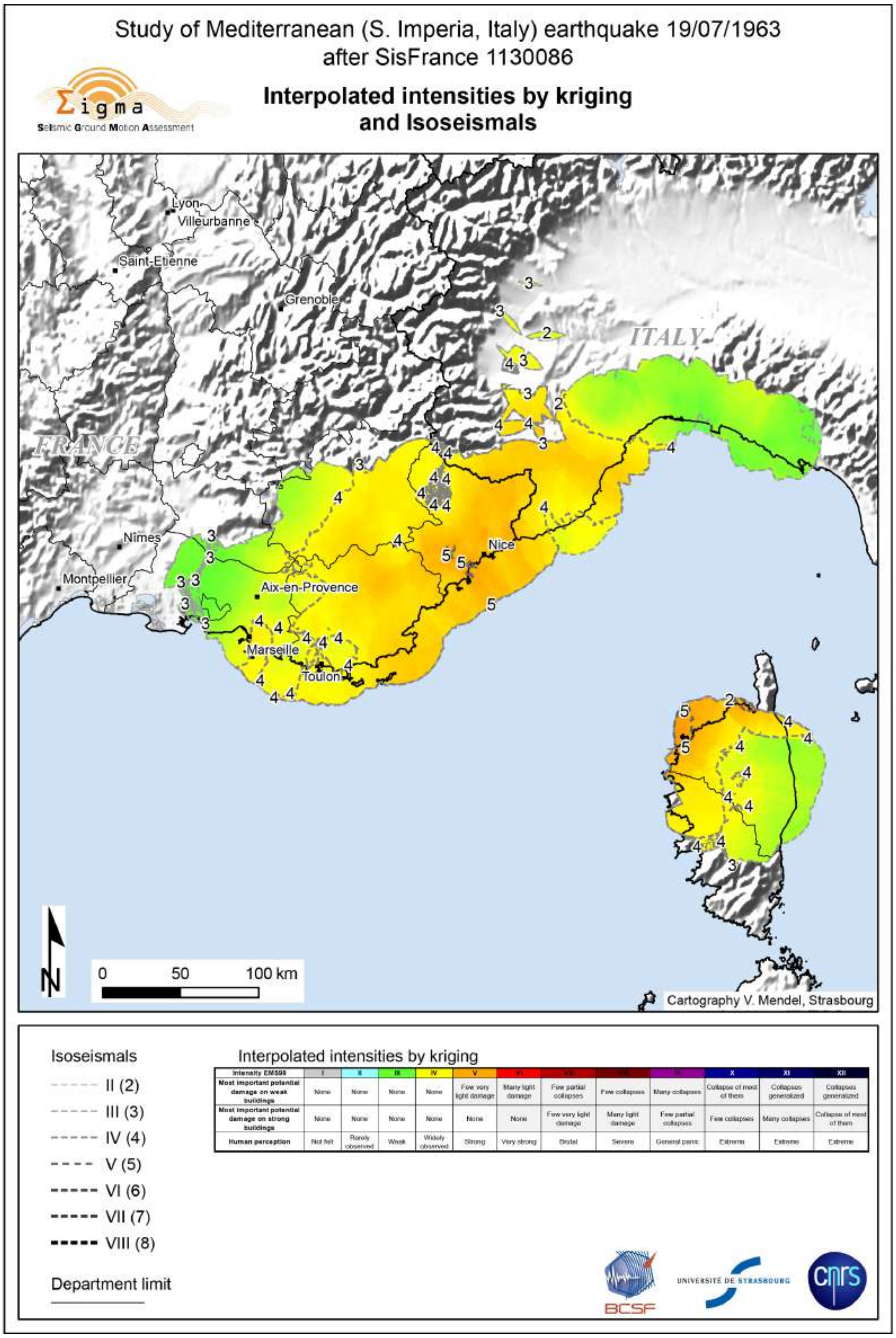
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit

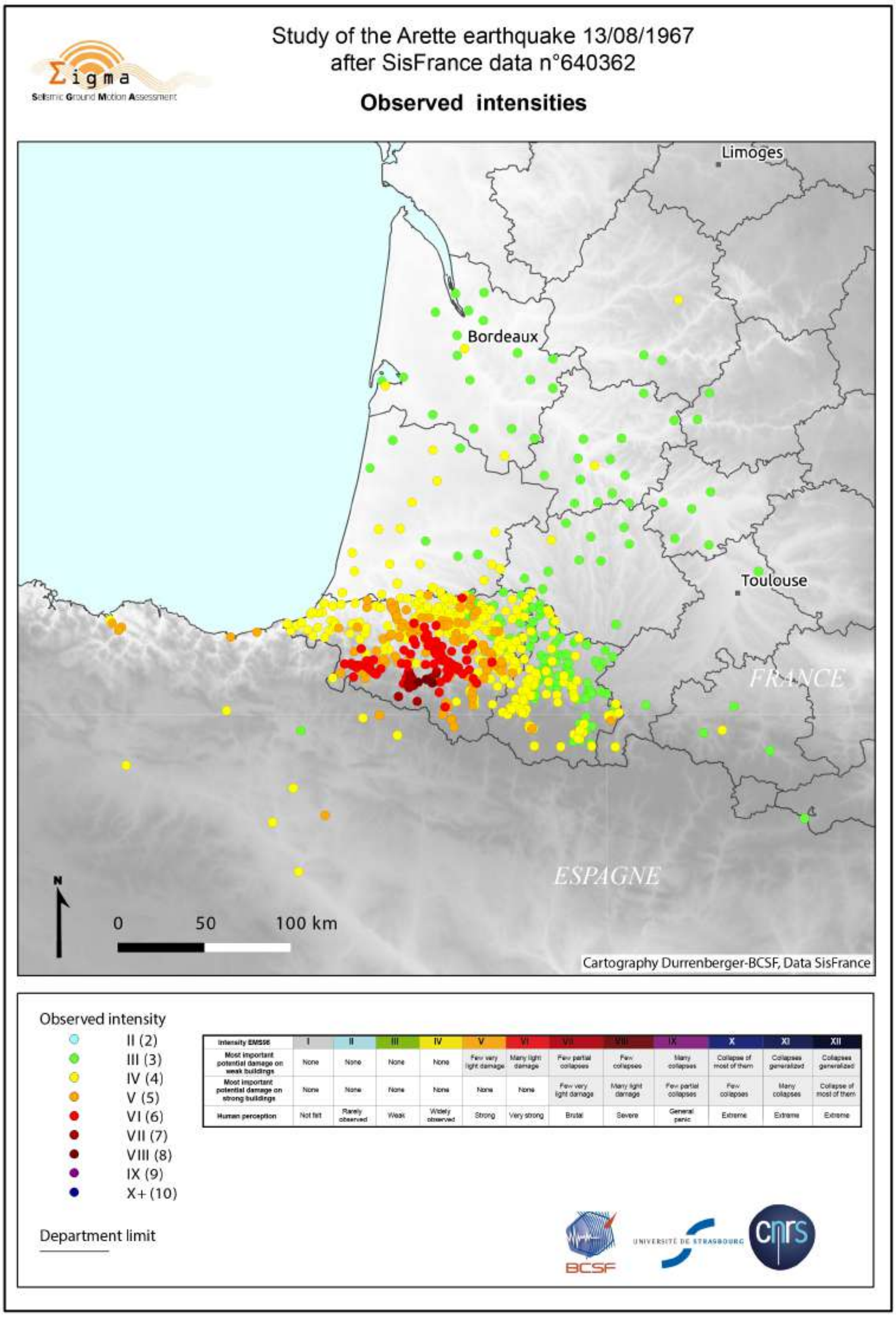


Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



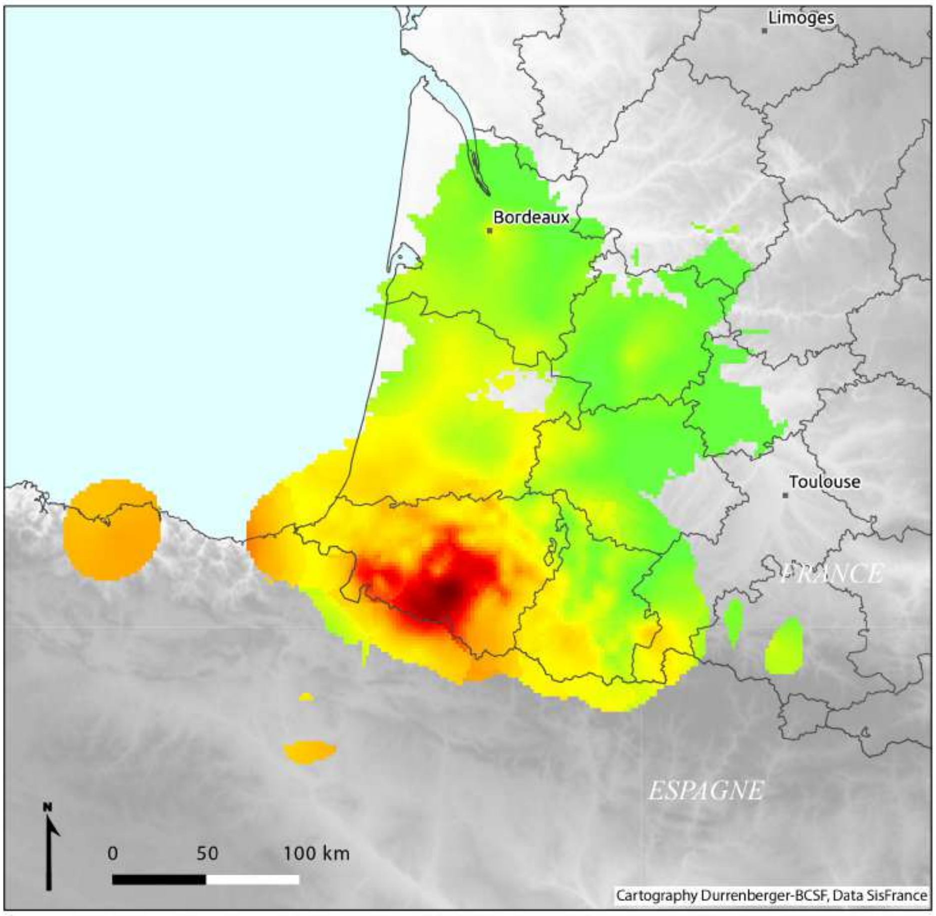
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1967-08-13: Arette earthquake, Mw=5.2, Depth=3km, Isoseismal-min (Kriging)=4.0



Study of the Arette earthquake 13/08/1967
after SisFrance data n°640362

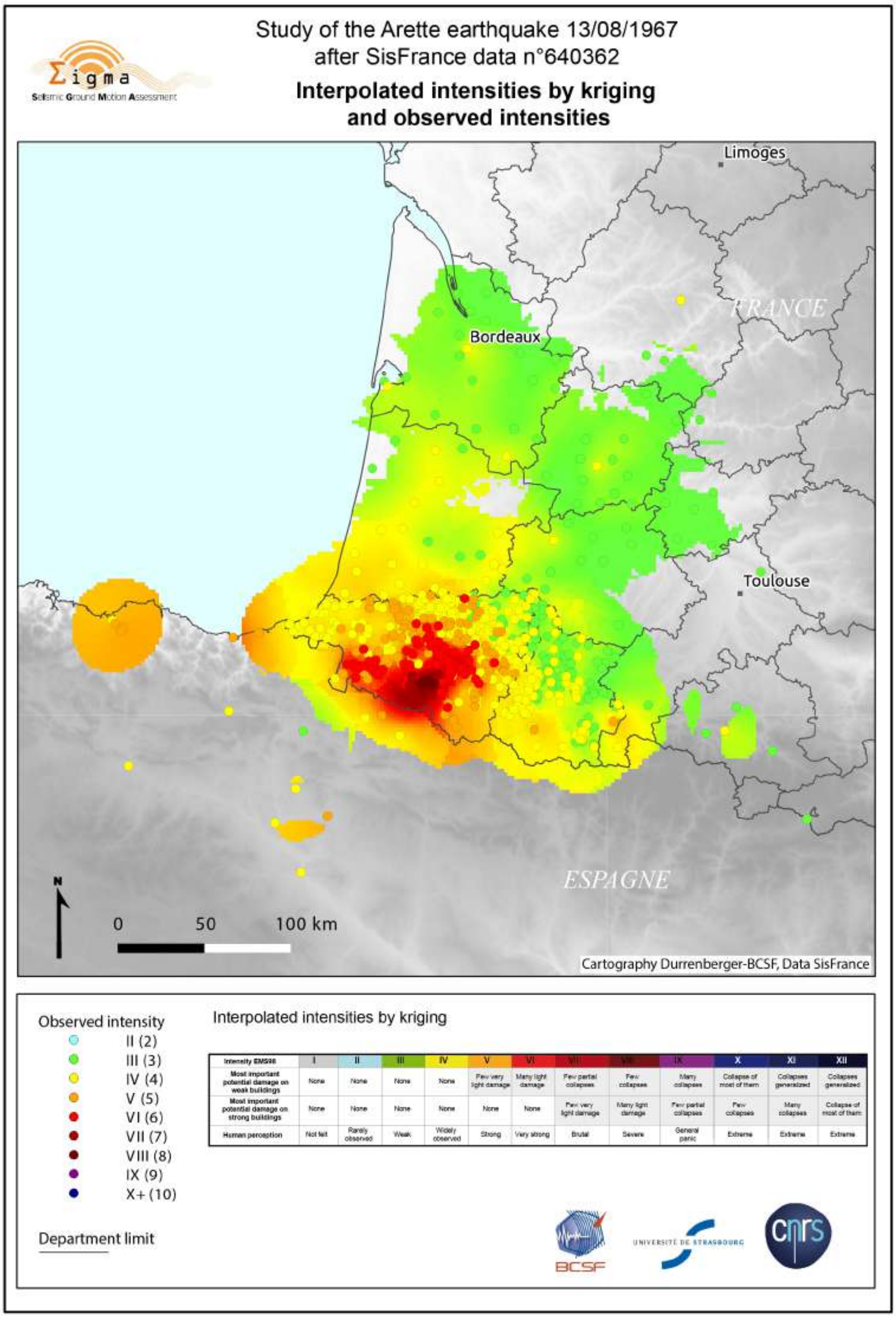
Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

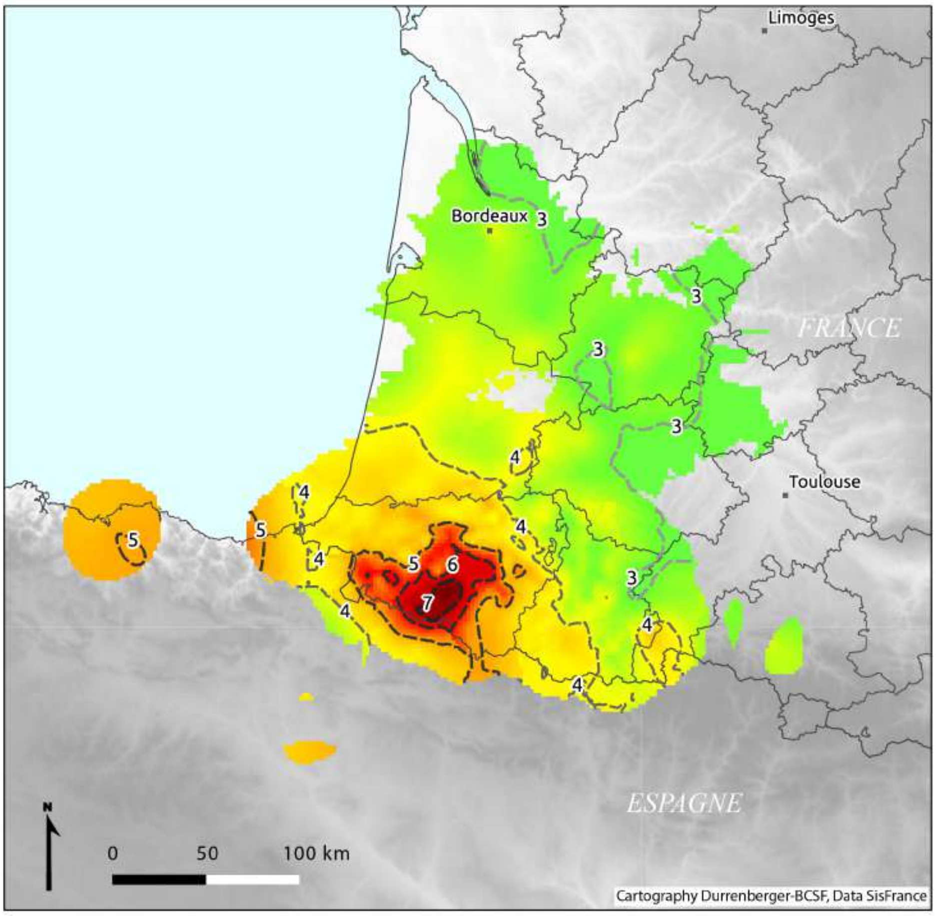
Department limit



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of the Arette earthquake 13/08/1967
after SisFrance data n°640362

Interpolated intensities by kriging and Isoseismals



Isoseismals

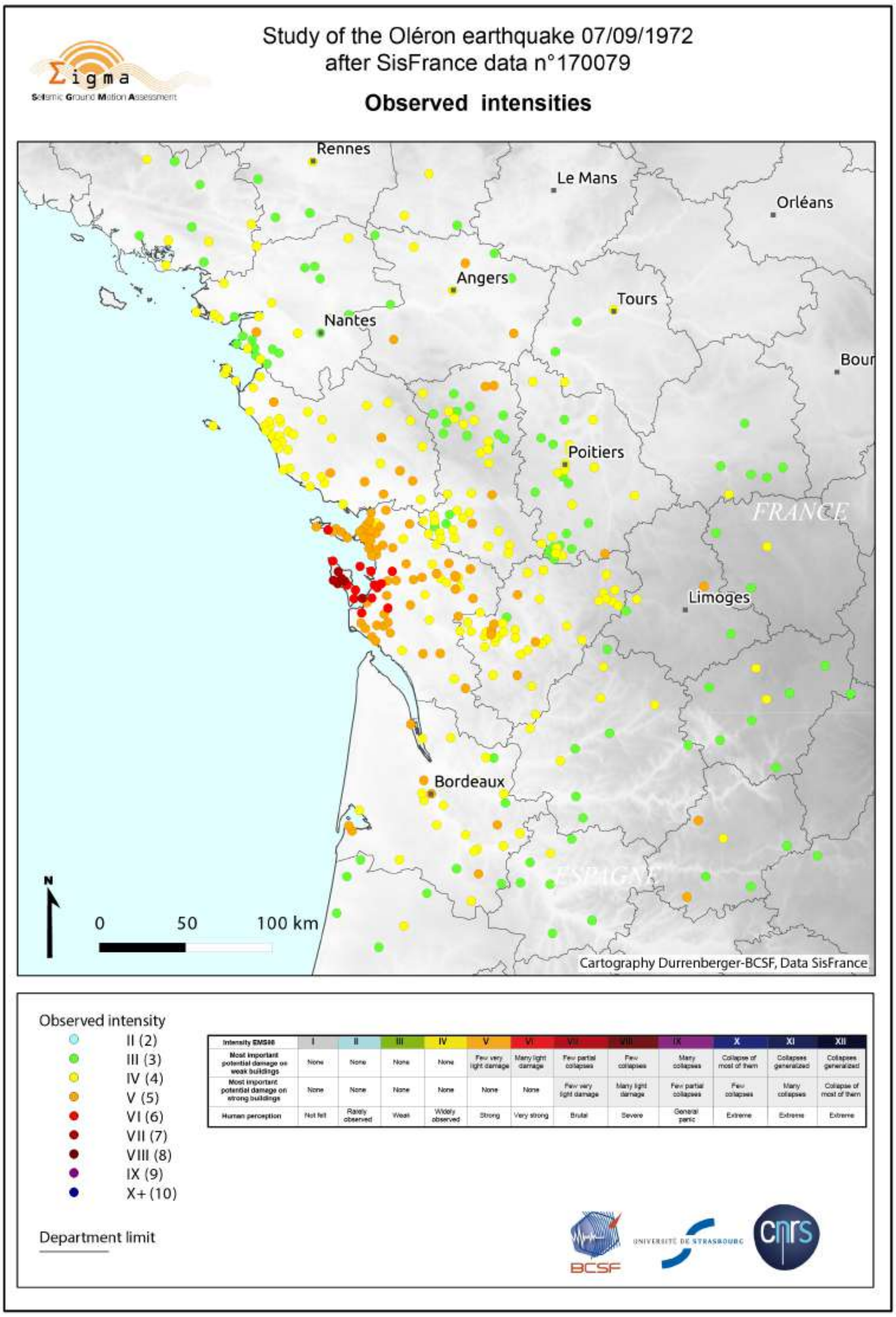
- II (2)
- III (3)
- IV (4)
- V (5)
- VI (6)
- VII (7)
- VIII (8)
- IX (9)
- X (10)

Department limit

Interpolated intensities by kriging

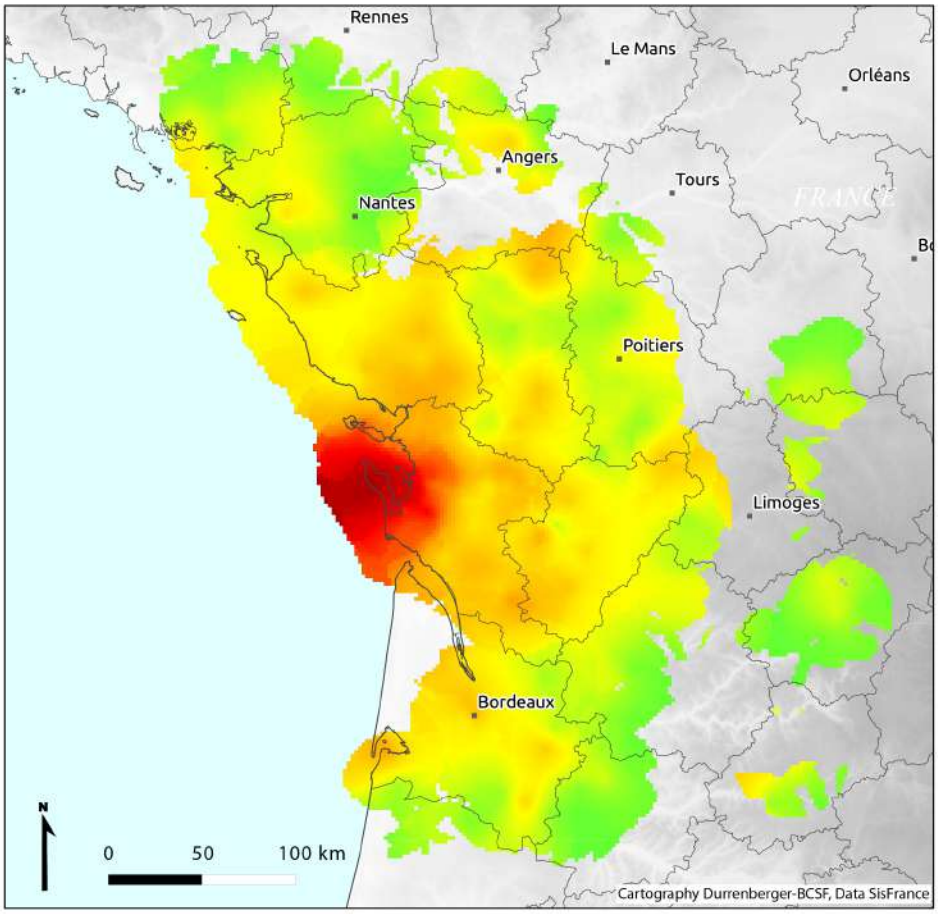
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1972-09-07: Oléron earthquake, Mw=5, Depth=11km, Isoseismal-min (Kriging)=4.0



Study of the Oléron earthquake 07/09/1972
after SisFrance data n°170079

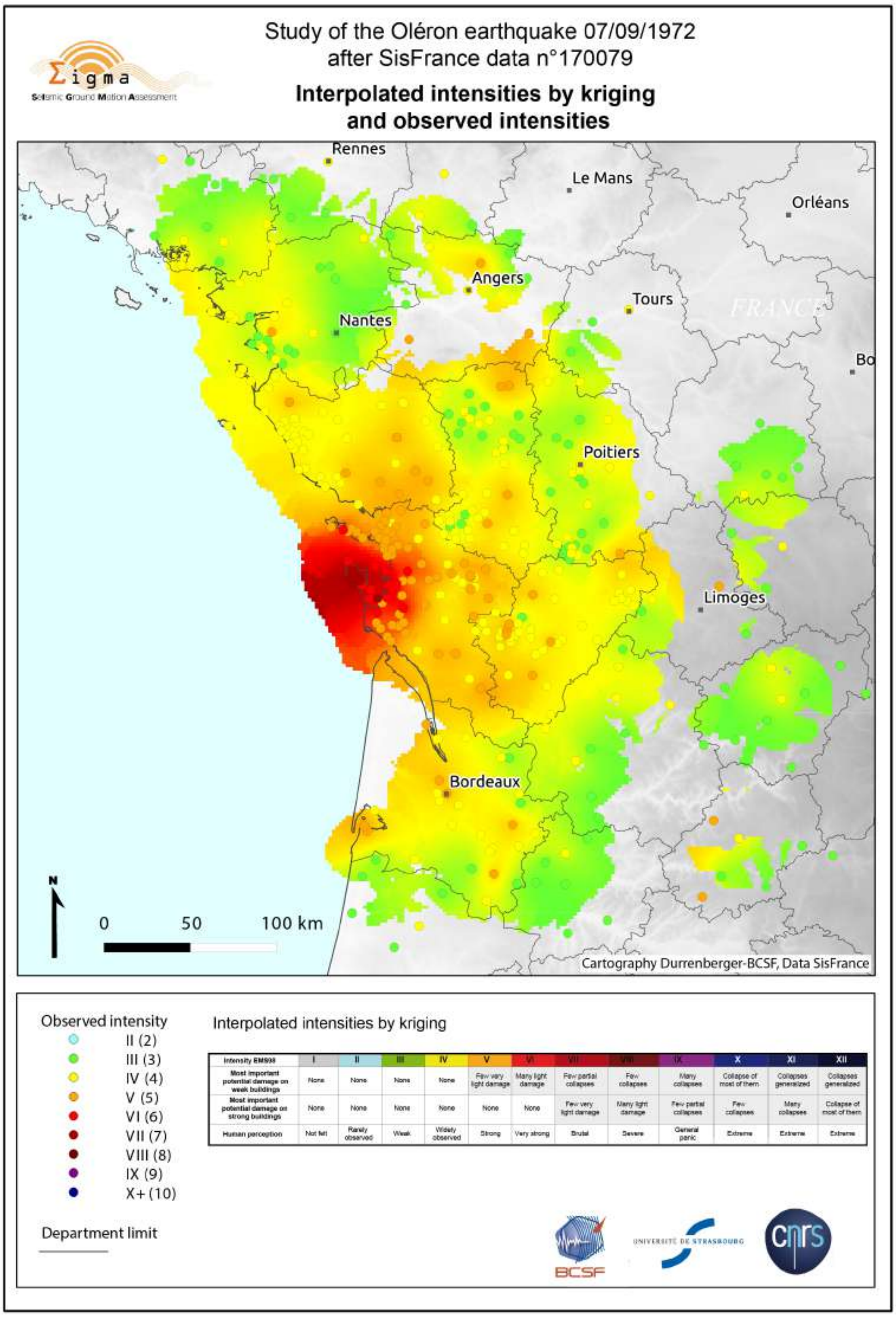
Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit



Study of the Oléron earthquake 07/09/1972
after SisFrance data n°170079
Interpolated intensities by kriging
and observed intensities
Sigma
Seismic Ground Motion Assessment
Rennes
Le Mans
Orléans
Angers
Tours
Nantes
FRANCE
Poitiers
Limoges
Bordeaux
N
0
50
100 km
Cartography Durrenberger-BCSF, Data SisFrance
Observed intensity
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X+ (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98: I, II, III, IV, V, VI, VII, VIII, IX, X, XI, XII
Most important potential damage on week buildings: None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them, Collapses generalized, Collapses generalized
Most important potential damage on strong buildings: None, None, None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them
Human perception: Not felt, Rarely observed, Weak, Widely observed, Strong, Very strong, Brutal, Severe, General panic, Extreme, Extreme, Extreme
BCSF
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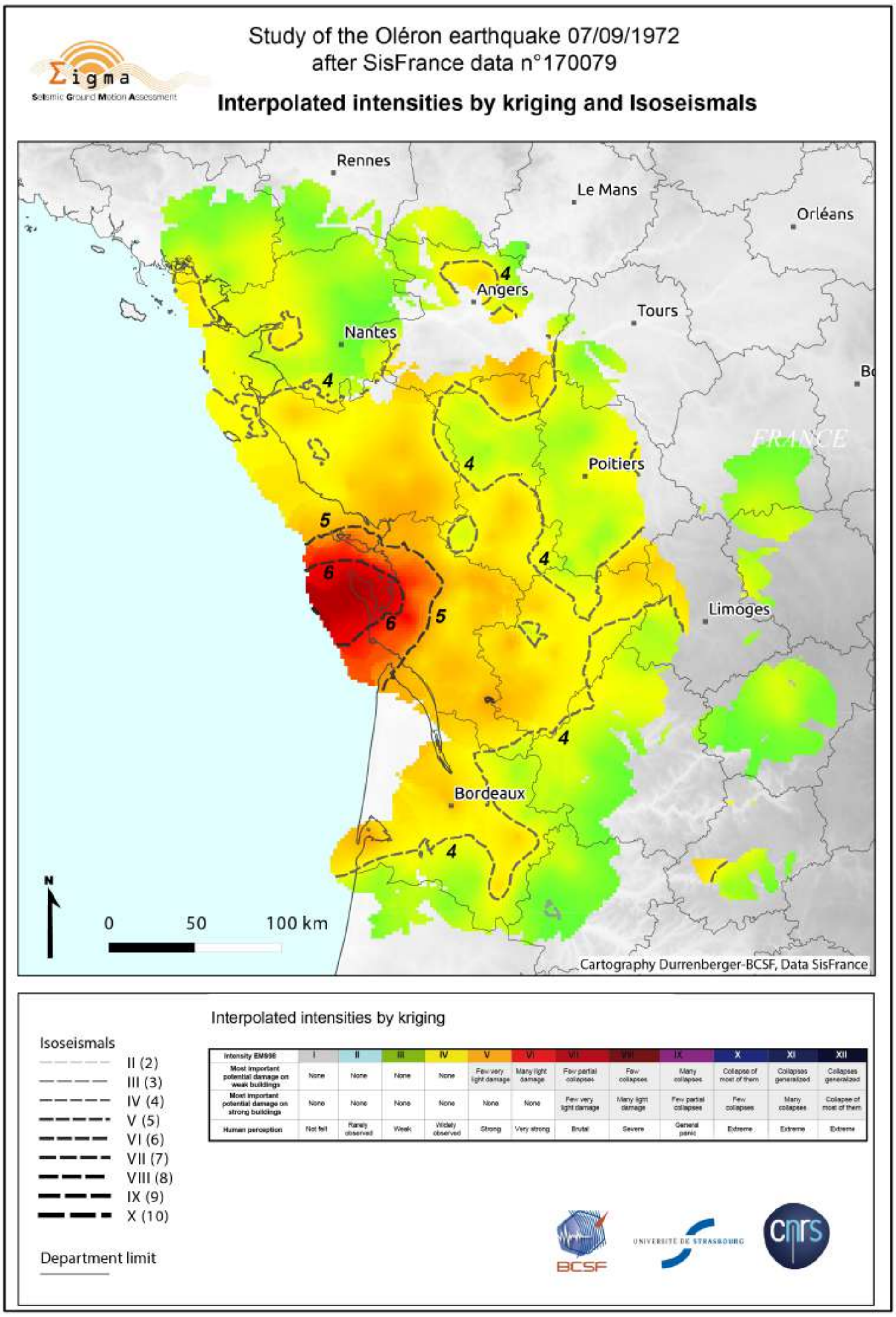
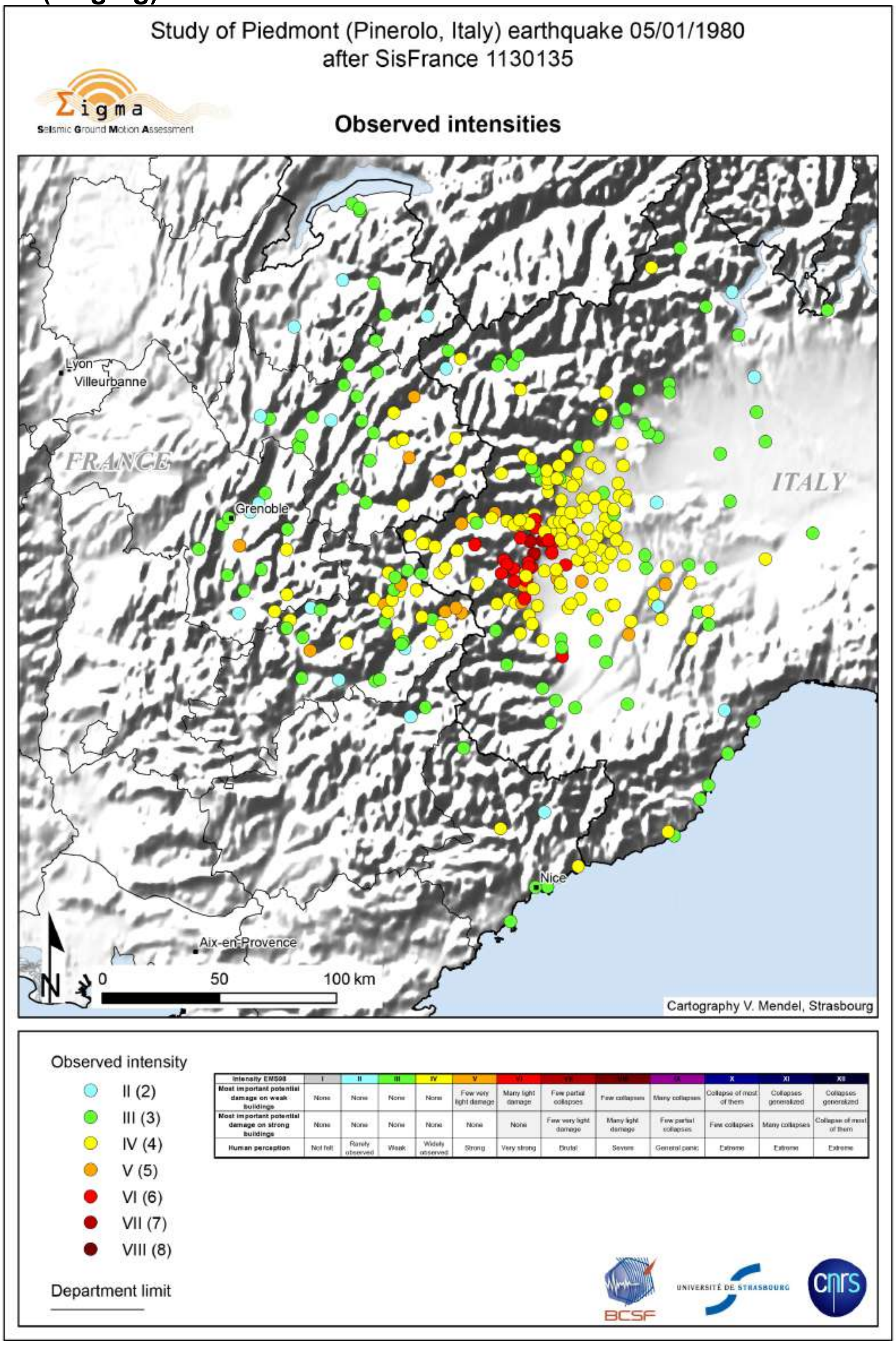
cnrs



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

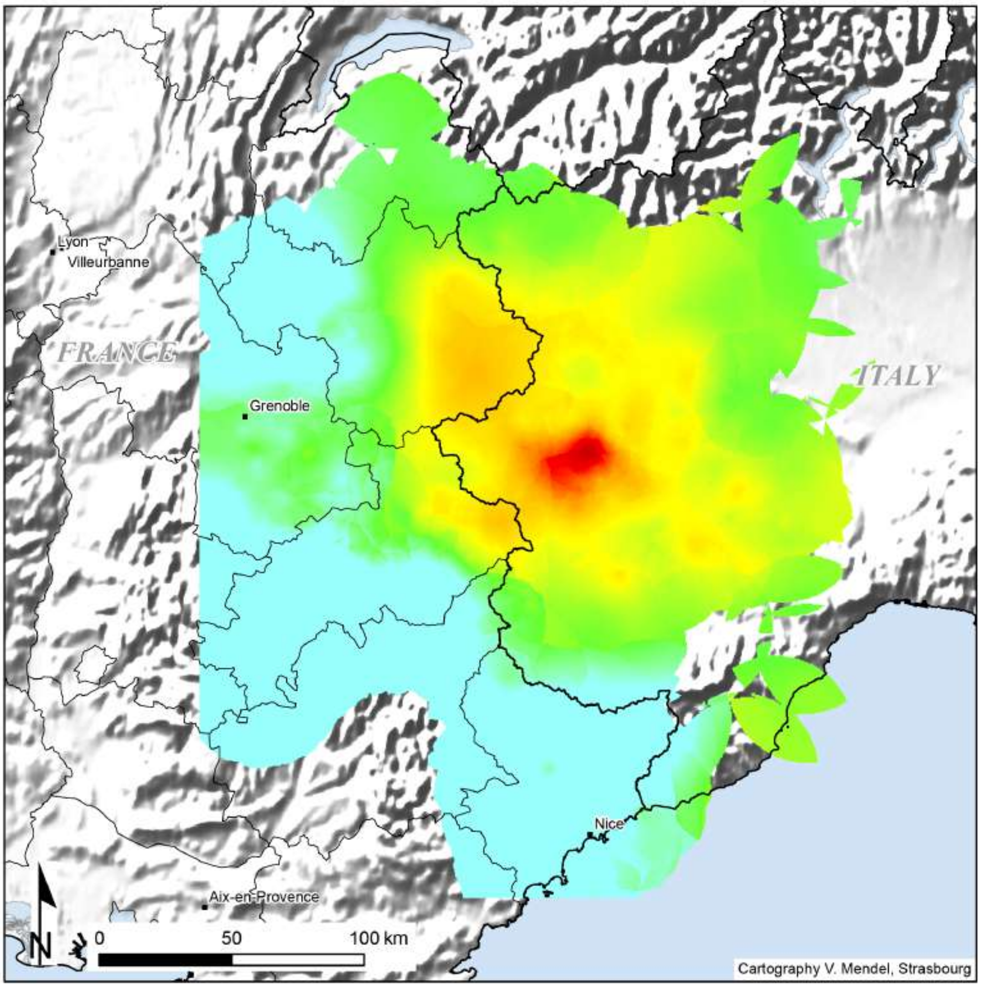
1980-01-05: Piedmont earthquake (Auto), Mw=4.5, Depth=10km, Isoseismal-min (Kriging)=3.5



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of Piedmont (Pinerolo, Italy) earthquake 05/01/1980
after SisFrance 1130135

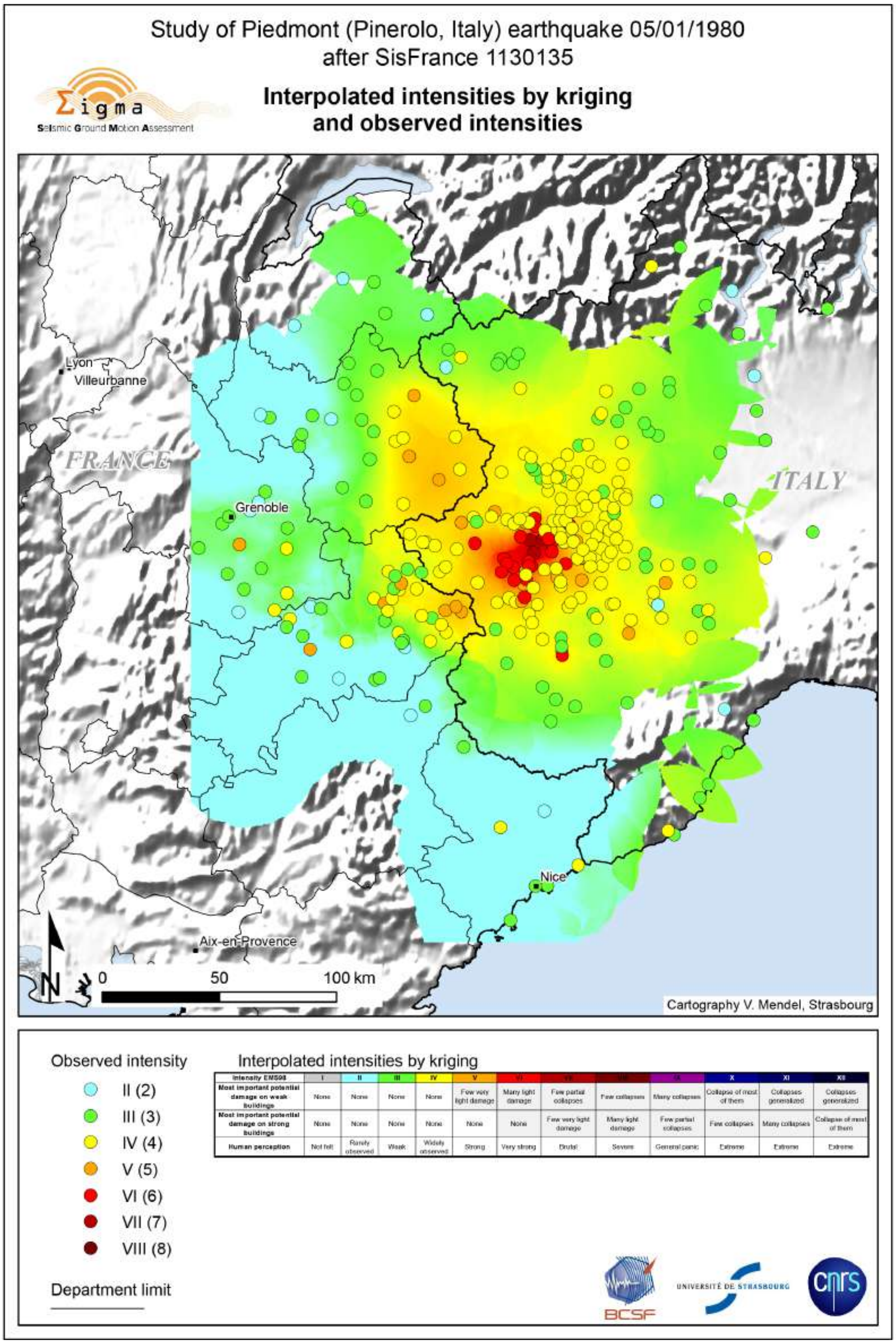
Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit


Study of Piedmont (Pinerolo, Italy) earthquake 05/01/1980
after SisFrance 1130135
Σigma
Seismic Ground Motion Assessment
Interpolated intensities by kriging
and observed intensities
Lyon
Villeurbanne
FRANCE
ITALY
Grenoble
Nice
Aix-en-Provence
N
0
50
100 km
Cartography V. Mendel, Strasbourg
Observed intensity
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
Department limit
Interpolated intensities by kriging
Intensity EMS98
I
II
III
IV
V
X
XI
XII
Most important potential damage on weak buildings
None
None
None
None
Few very light damage
Many light damage
Few partial collapses
Few collapses
Many collapses
Collapse of most of them
Collapses generalized
Collapses generalized
Most important potential damage on strong buildings
None
None
None
None
None
None
Few very light damage
Many light damage
Few partial collapses
Few collapses
Many collapses
Collapse of most of them
Human perception
Not felt
Rarely observed
Weak
Widely observed
Strong
Very strong
Brutal
Severe
General panic
Extreme
Extreme
Extreme
BCSF
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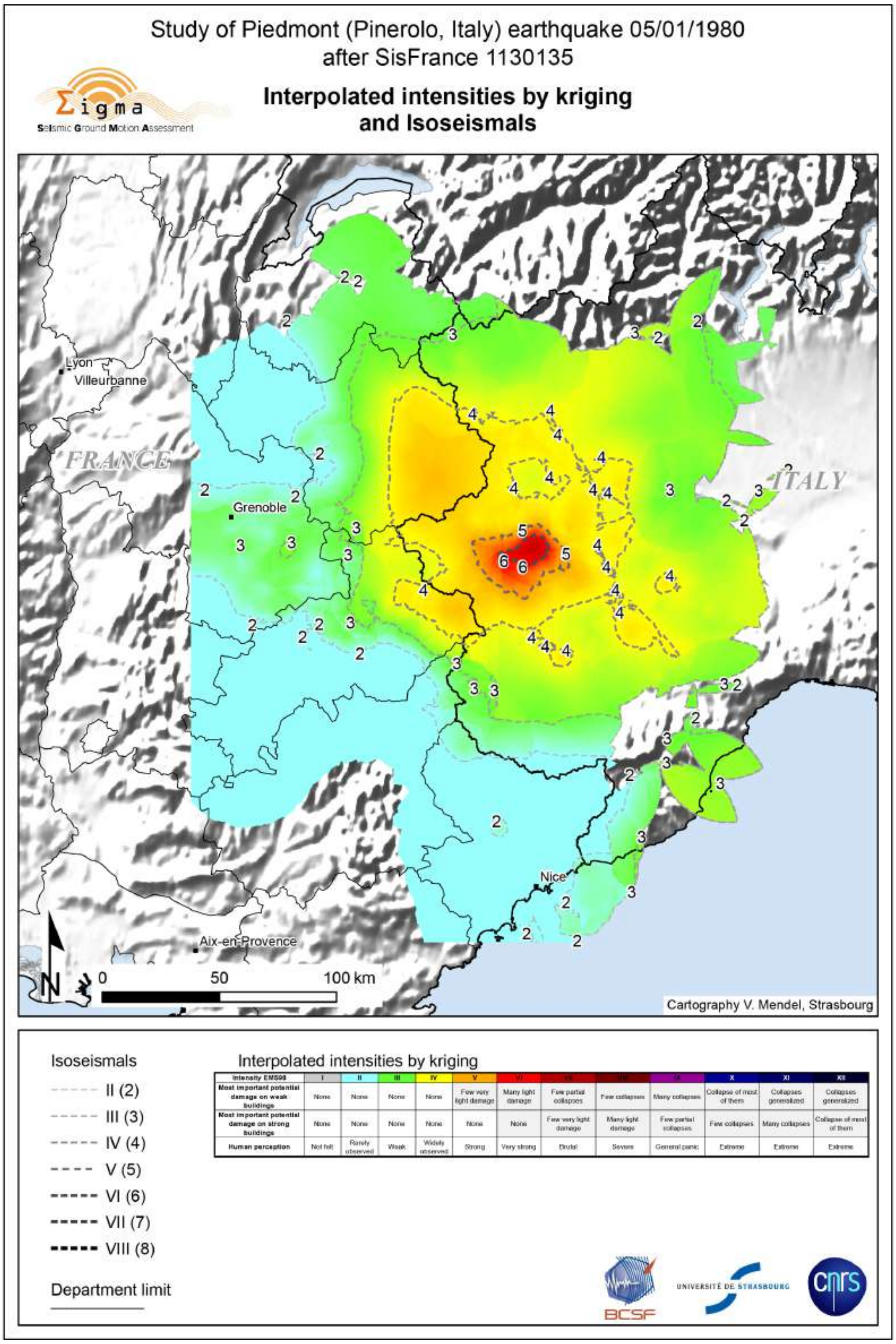
cnrs


Study of Piedmont (Pinerolo, Italy) earthquake 05/01/1980
after SisFrance 1130135
Interpolated intensities by kriging
and Isoseismals
Lyon
Villeurbanne
FRANCE
ITALY
Grenoble
Nice
Aix-en-Provence
0
50
100 km
Cartography V. Mendel, Strasbourg
Isoseismals
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
Department limit
Interpolated intensities by kriging
Intensity EMS98: I, II, III, IV, V, X, XI, XII
Most important potential damage on weak buildings: None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them, Collapses generalized, Collapses generalized
Most important potential damage on strong buildings: None, None, None, None, None, None, Few very light damage, Many light damage, Few partial collapses, Few collapses, Many collapses, Collapse of most of them
Human perception: Not felt, Rarely observed, Weak, Widely observed, Strong, Very strong, Brutal, Severe, General panic, Extreme, Extreme, Extreme
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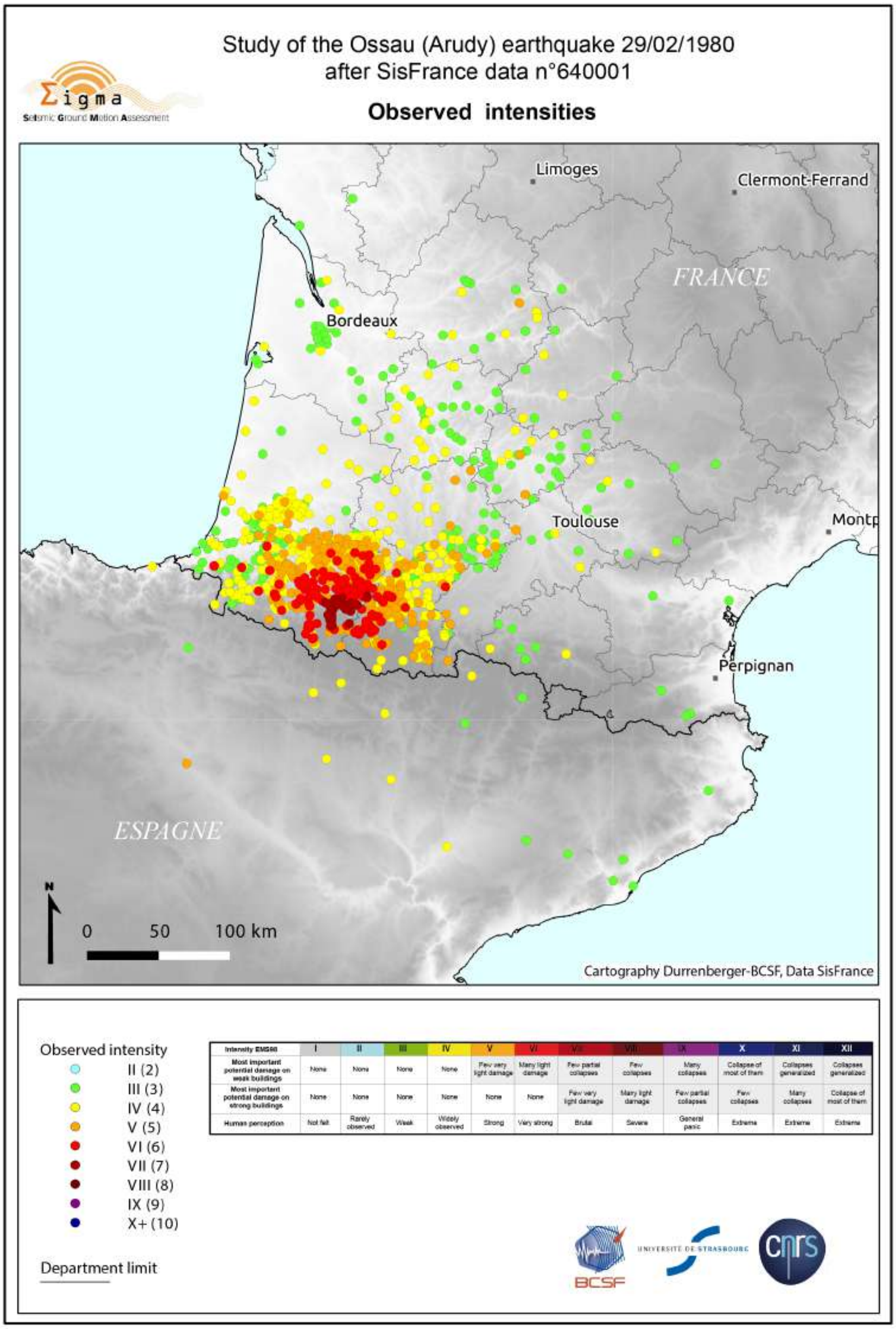
CNRS

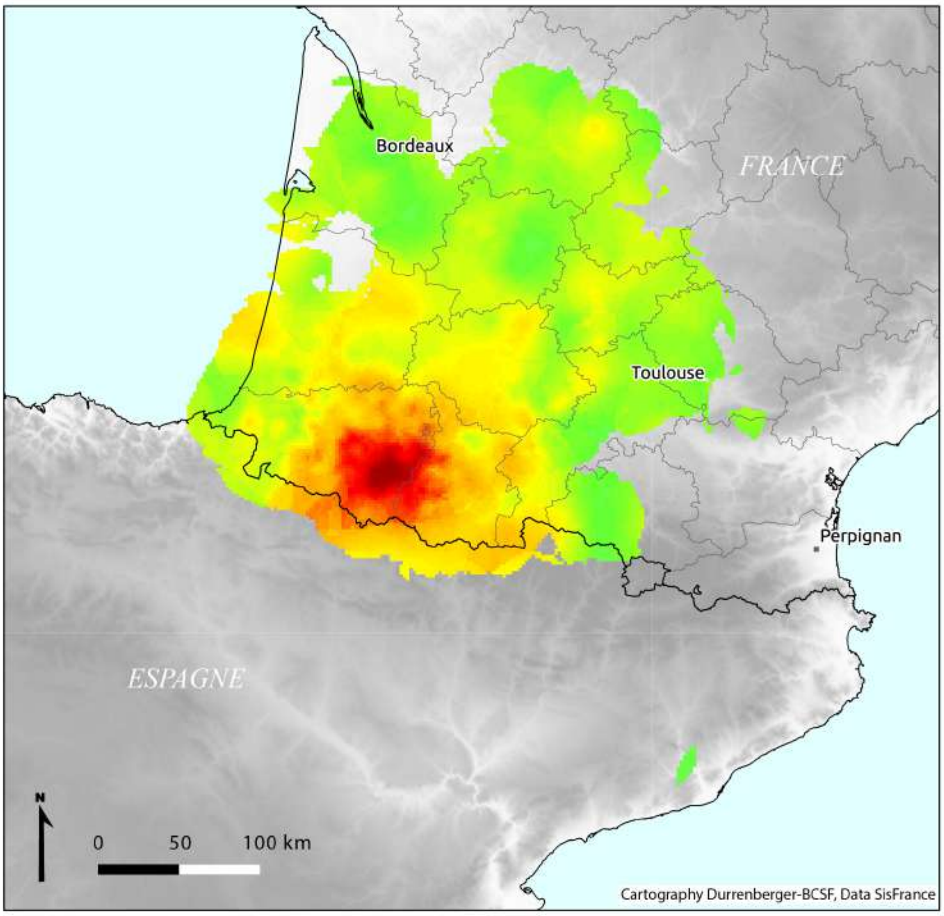
1980-02-29: Ossau earthquake, Mw=5, Depth=5.4km, Isoseismal-min (Kriging)=4.5



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of the Ossau (Arudy) earthquake 29/02/1980
after SisFrance data n°640001

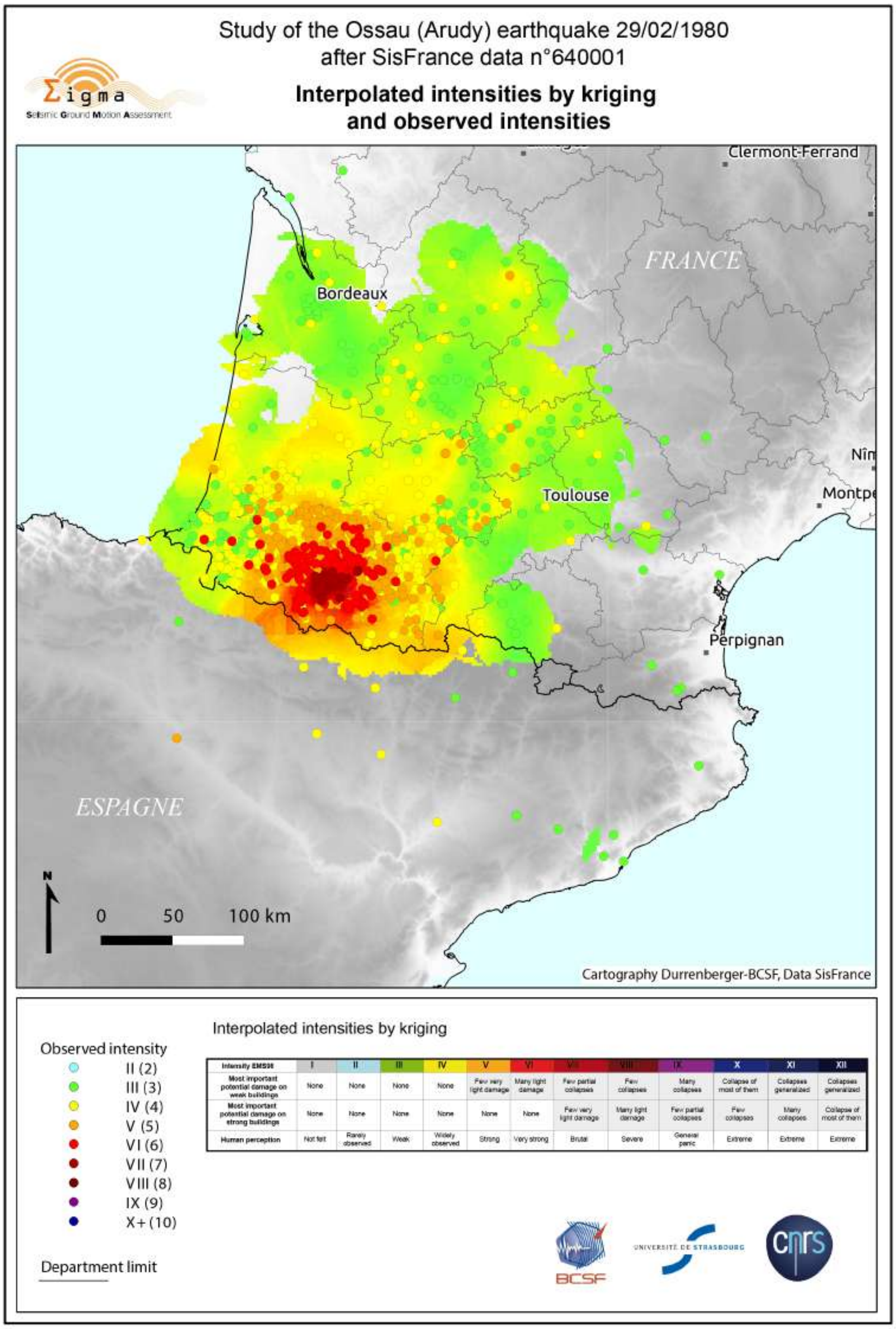
Interpolated intensities by kriging



Interpolated intensities by kriging

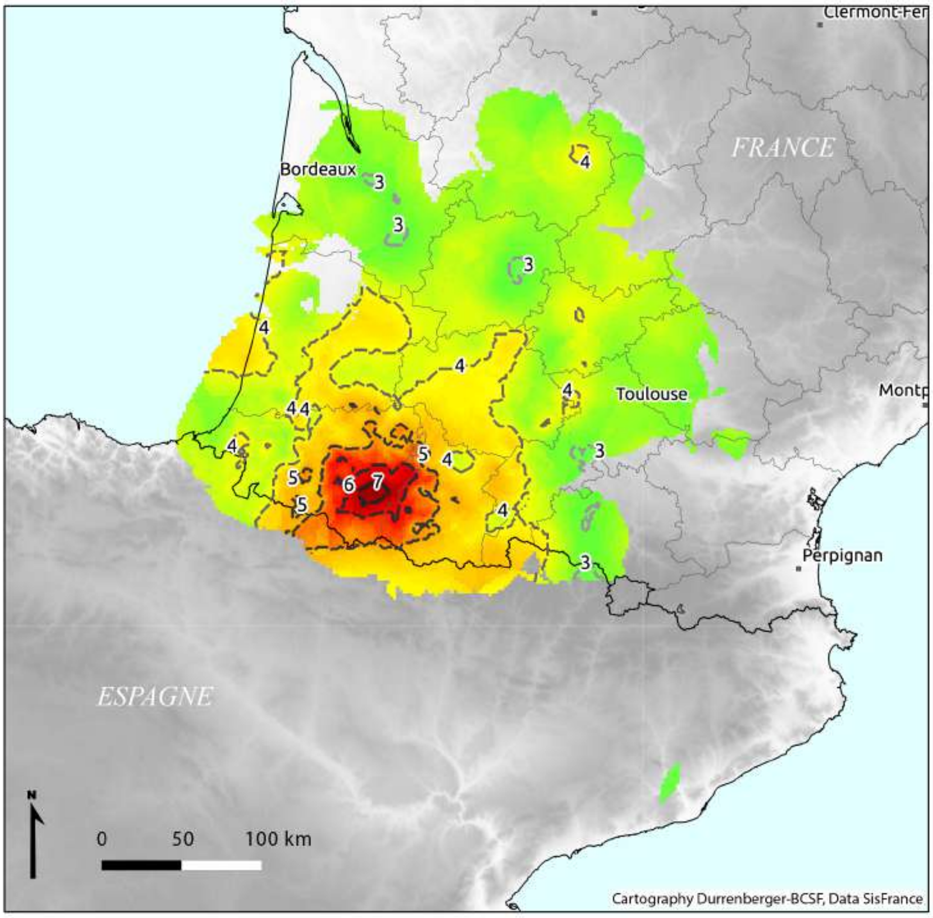
Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit


Study of the Ossau (Arudy) earthquake 29/02/1980
after SisFrance data n°640001
Interpolated intensities by kriging
and observed intensities
Clermont-Ferrand
FRANCE
Bordeaux
Toulouse
Montpe
Perpignan
ESPAGNE
N
0 50 100 km
Cartography Durrenberger-BCSF, Data SisFrance
Observed intensity
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X+ (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98 | I | II | III | IV | V | VI | X | XI | XII
Most important potential damage on weak buildings | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them | Collapses generalized | Collapses generalized
Most important potential damage on strong buildings | None | None | None | None | None | None | Few very light damage | Many light damage | Few partial collapses | Few collapses | Many collapses | Collapse of most of them
Human perception | Not felt | Rarely observed | Weak | Widely observed | Strong | Very strong | Brutal | Severe | General panic | Extreme | Extreme | Extreme
UNIVERSITÉ DE STRASBOURG

Study of the Ossau (Arudy) earthquake 29/02/1980
after SisFrance data n°640001

Interpolated intensities by kriging and Isoseismals



Isoseismals

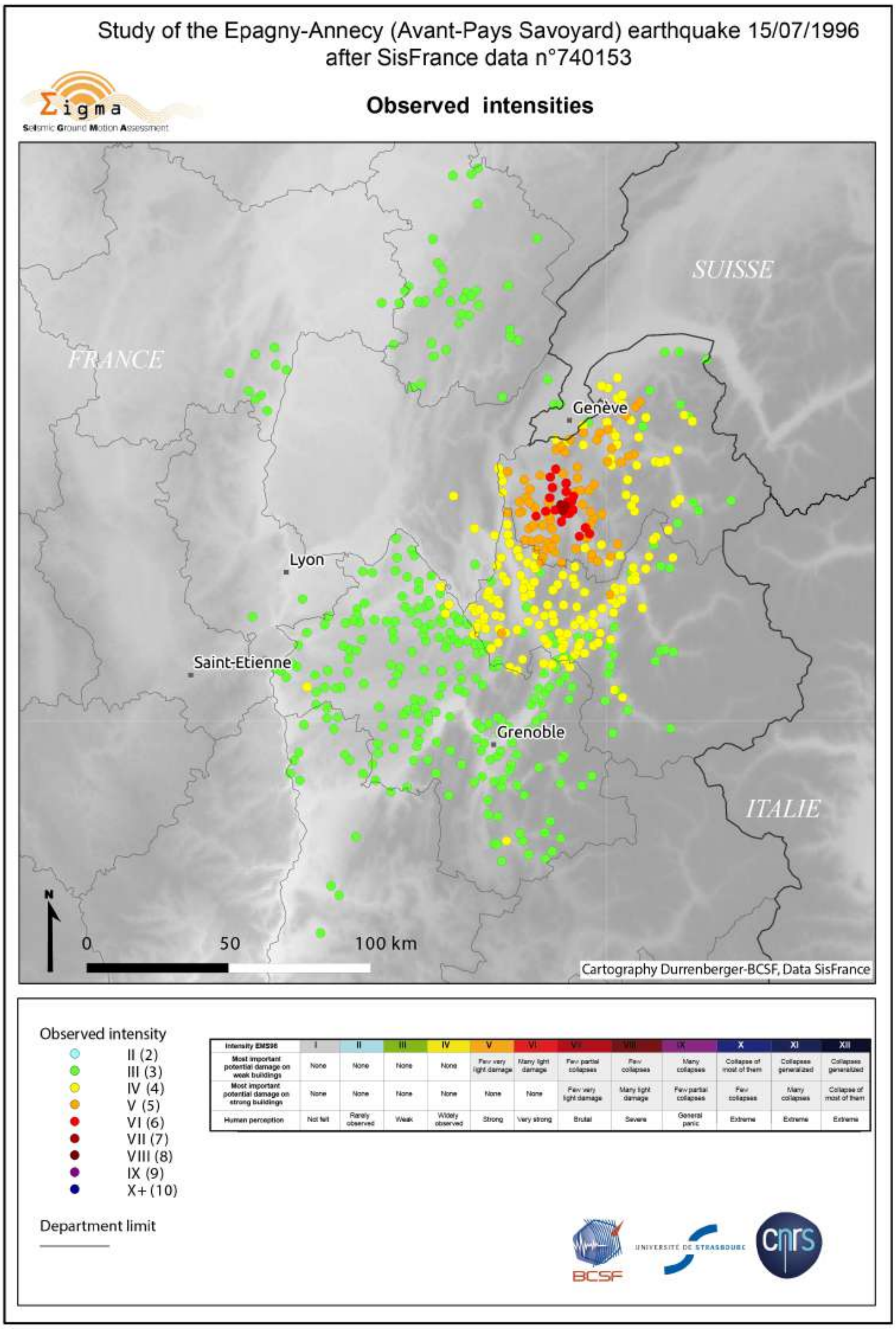
- II (2)
- III (3)
- IV (4)
- V (5)
- VI (6)
- VII (7)
- VIII (8)
- IX (9)
- X (10)

Department limit

Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

1996-07-15: Epagny-Annecy earthquake, Mw=4.9, Depth=3km, Isoseismal-min (Kriging)=3.5



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
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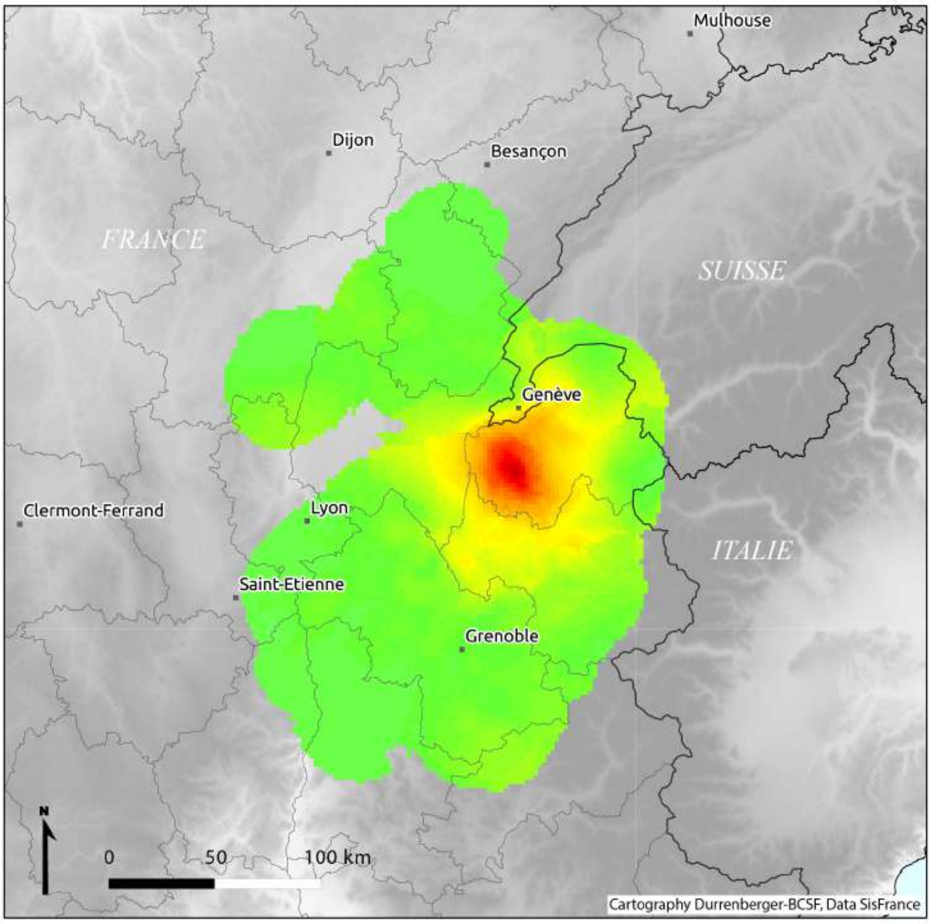
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Study of the Epagny-Annecy (Avant-Pays Savoyard) earthquake 15/07/1996
after SisFrance data n°740153

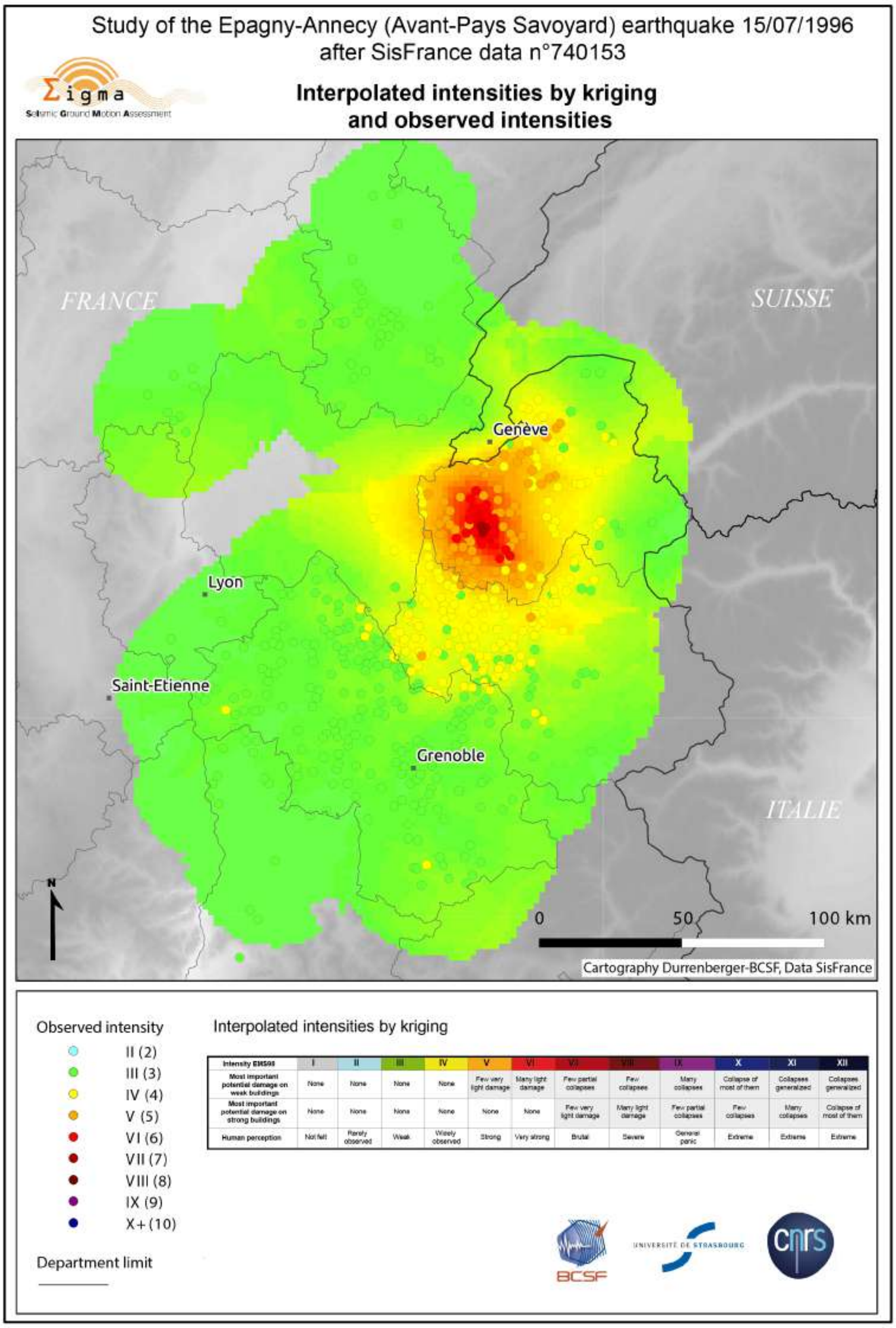
Interpolated intensities by kriging



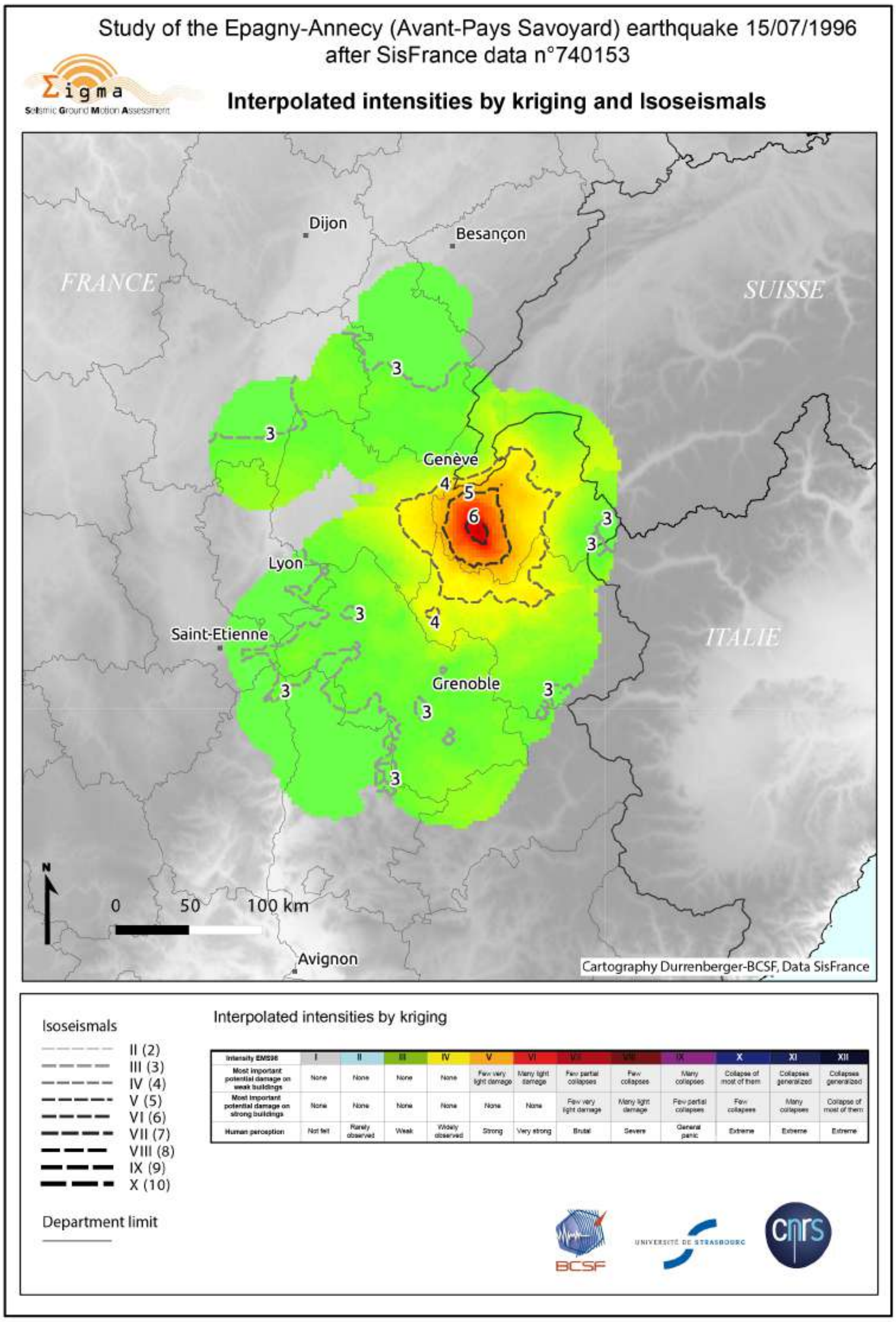
Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme



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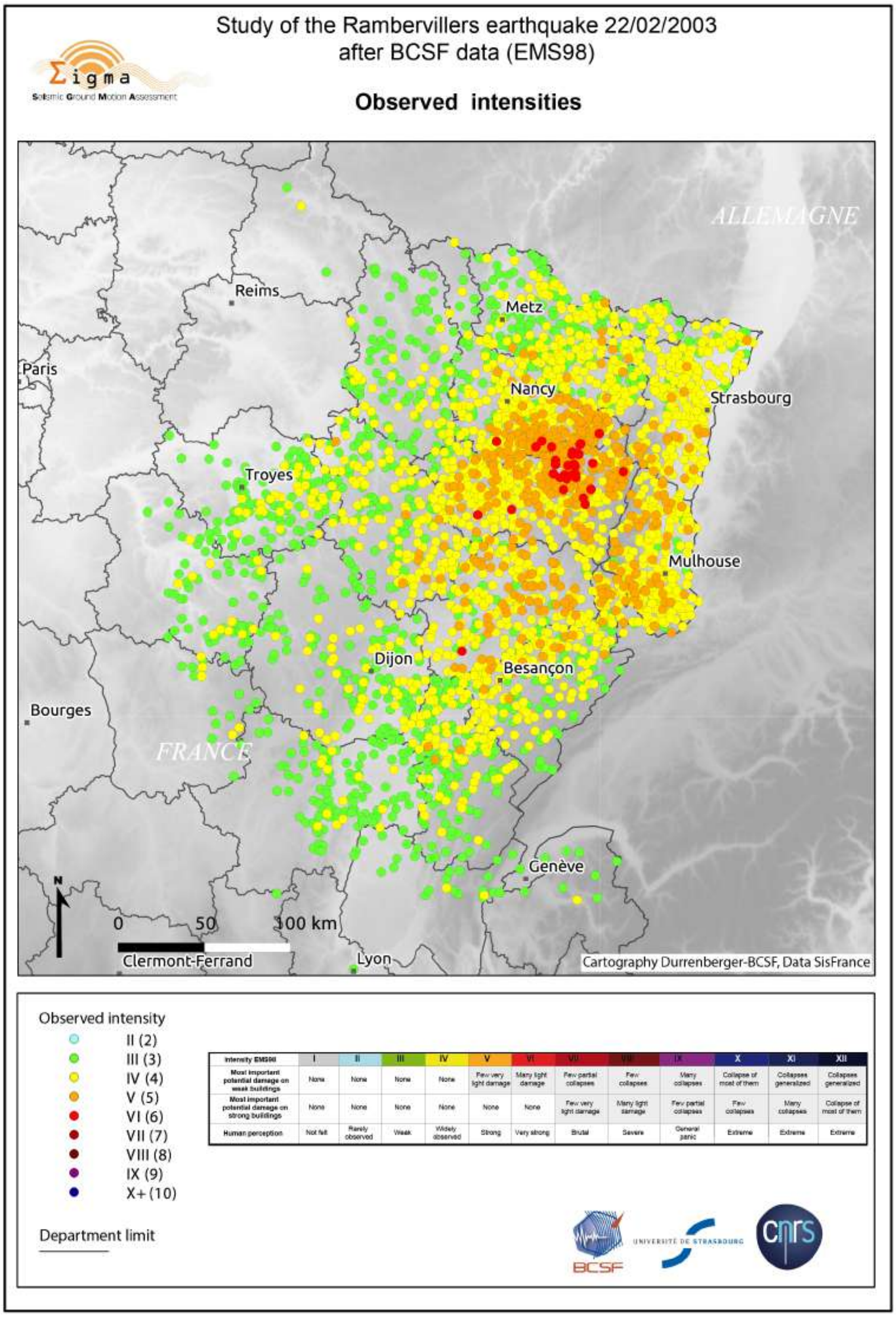
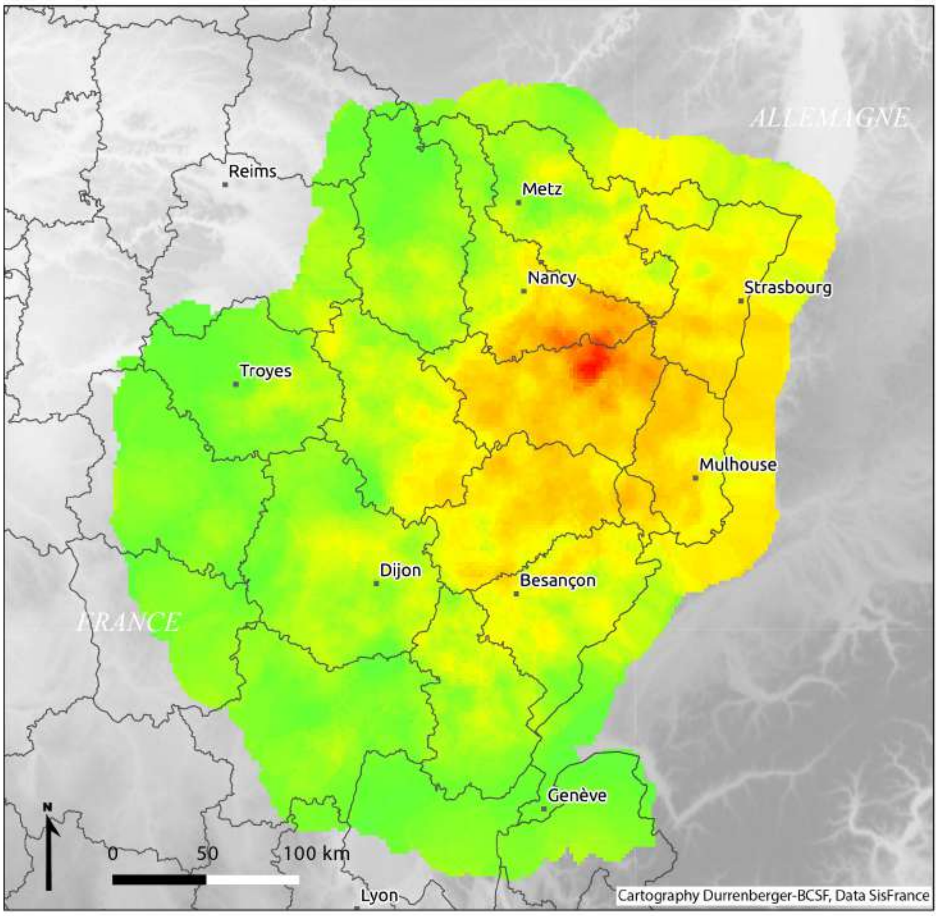
Most important potential damage on strong buildings	None	None	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

2003-02-22: Rambervillers earthquake, Mw=4.9, Depth=12km, Isoseismal-min (Kriging)=3.8



Study of the Rambervillers earthquake 22/02/2003
after BCSF data (EMS98)

Interpolated intensities by kriging



Interpolated intensities by kriging

Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
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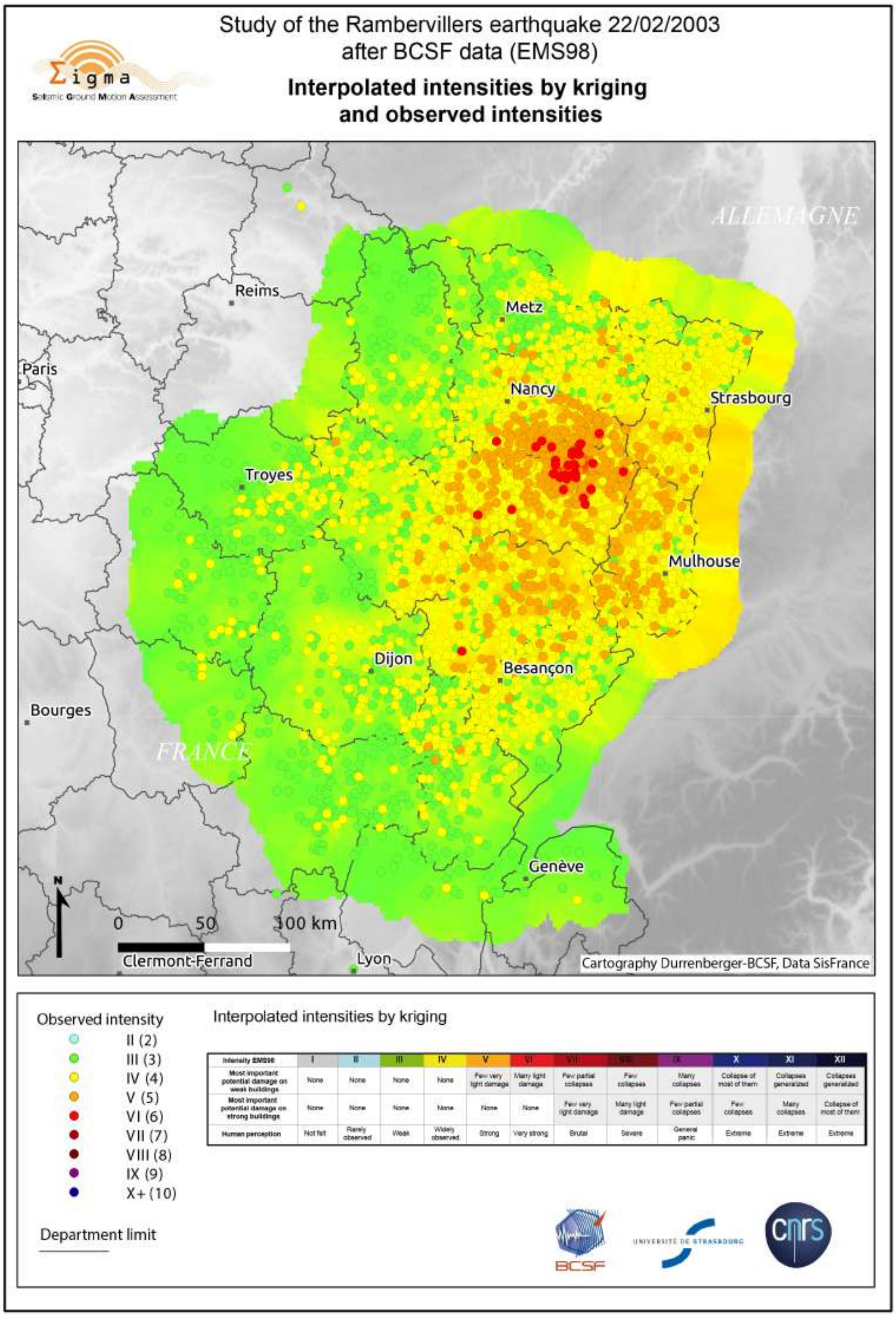
Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

Department limit



Study of the Rambervillers earthquake 22/02/2003
after BCSF data (EMS98)
Interpolated intensities by kriging
and observed intensities
Σigma
Seismic Ground Motion Assessment
ALLEMAGNE
Reims
Metz
Paris
Nancy
Strasbourg
Troyes
Mulhouse
Dijon
Besançon
Bourges
FRANCE
Genève
N
0
50
100 km
Clermont-Ferrand
Lyon
Cartography Durrenberger-BCSF, Data SisFrance
Observed intensity
II (2)
III (3)
IV (4)
V (5)
VI (6)
VII (7)
VIII (8)
IX (9)
X+ (10)
Department limit
Interpolated intensities by kriging
Intensity EMS98 | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII
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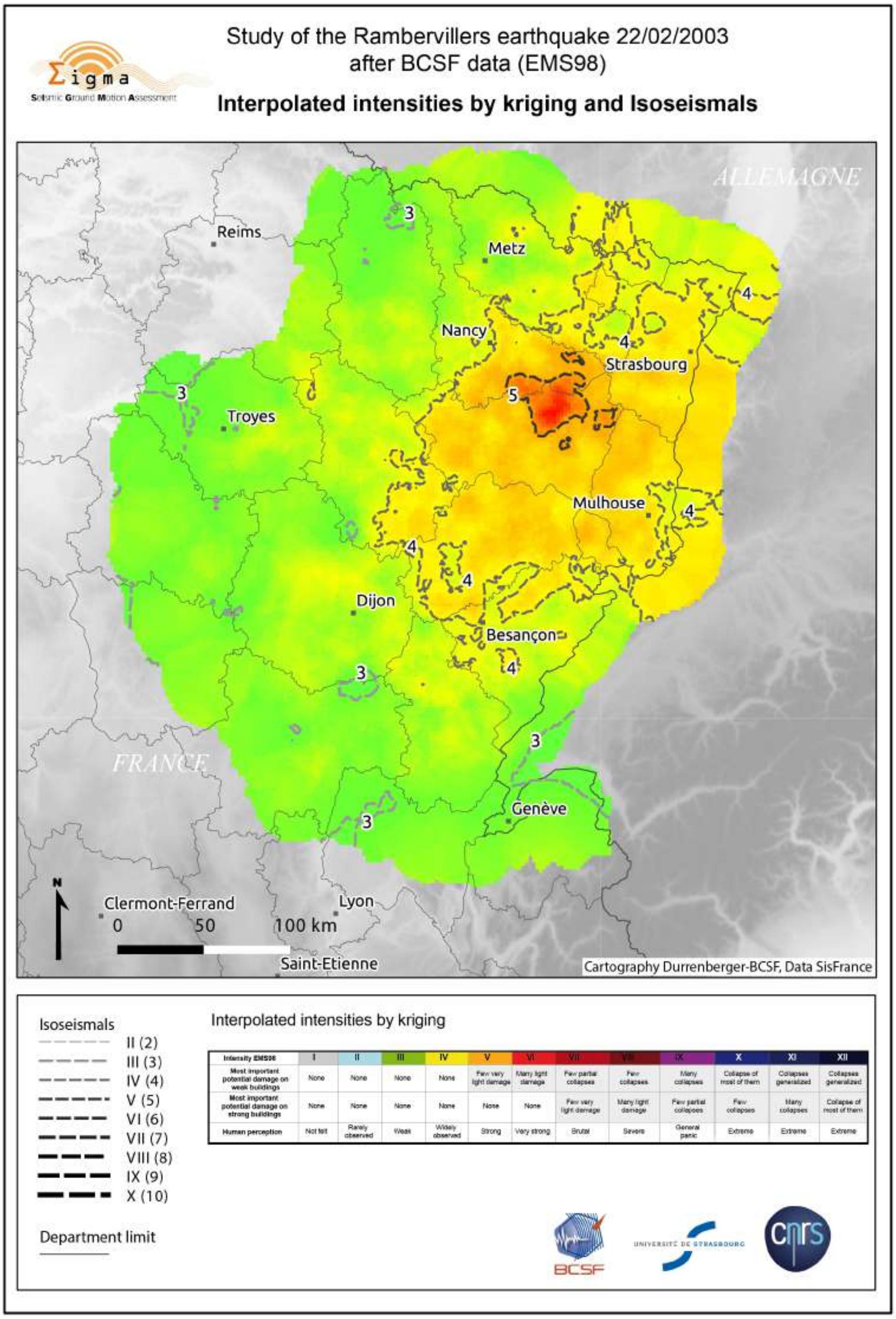
Human perception | Not felt | Rarely observed | Weak | Widely observed | Strong | Very strong | Brutal | Severe | General panic | Extreme | Extreme | Extreme
BCSF
UNIVERSITÉ DE STRASBOURG
CNRS



Intensity EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Most important potential damage on weak buildings	None	None	None	None	Few very light damage	Many light damage	Few partial collapses	Few collapses	Many collapses	Collapse of most of them	Collapses generalized	Collapses generalized
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Human perception	Not felt	Rarely observed	Weak	Widely observed	Strong	Very strong	Brutal	Severe	General panic	Extreme	Extreme	Extreme

References

Bakun W. H., A. Gómez Capera, M. Stucchi (2011) Epistemic Uncertainty in the Location and Magnitude of Earthquakes in Italy from Macroseismic Data, Bulletin of the Seismological Society of America, v. 101 no. 6 p. 2712-2725.

Bakun W.H. and Scotti O. (2006). Regional intensity attenuation models for France and the estimation of magnitude and location of historical earthquakes. Geophysical Journal International 164 (3), pp. 596-610.

Baumont D. et O. Scotti , (1999). Calibration en Ms et Mw d'une relation d'atténuation en intensité pour l'estimation des caractéristiques des séismes historiques en France métropolitaine, Bureau d'évaluation des risques sismiques pour la sûreté des installations, IRSN, 7ème colloque national.

Bretherton, F.B., R.E. Davis and C.B. Fandry. (1976). A technique for objective analysis and design of oceanographic experiments applied to MODE-73. Deep-Sea Res., 23, 559-582.

Camelbeeck T. (1993) : Mécanisme au foyer des tremblements de terre et contraintes tectoniques : le cas de la zone intraplaque belge" - Bruxelles -.

Cara, M., Cansi, Y., Schlupp, A. et al., 2015. SI-Hex: a new catalogue of instrumental seismicity for metropolitan France. Bull. Soc. géol. France, 2015, t. 186, no 1, pp. 3-19, doi:10.2113/gssgfbull.186.1.3.

Cara M., P.J. Alasset and C. Sira. (2008). Magnitude of historical earthquakes, from macroseismic data to seismic waveform modelling: application to the Pyrenees and a 1905 earthquake in the Alps. Historical Seismology Interdisciplinary Studies of Past and Recent Earthquakes Series: Modern Approaches in Solid Earth Sciences , Vol. 2, Fréchet J., Meghraoui M. & Stucchi M. (Eds), Springer.

Cara M, Schlupp A, Sira C (2007) Observations sismologiques : Sismicité de la France en 2003, 2004, 2005, Bureau Central Sismologique Français, ULP/EOST-CNRS/INSU, Strasbourg, 200p.

Cara M., W. Brüstle, M. Gisler, P. Kästli, C. Sira, C. Weihermüller et J. Lambert, (2005). Transfrontier macroseismic observations of the Ml=5.4 earthquake of February 22, 2003 at Rambervillers, France, Journal of Seismology, 9, p. 317-328.

Carr J. R. and Ch. E. Glass (1985) Treatment of earthquake ground motion using regionalized variables, Mathematical Geology, Volume 17, Number 3, 221-241.

Davis, J. C. (1986). Statistics and Data Analysis in Geology. 2nd ed, John Wiley & Sons. New York, 289 p.

Denieul M., Sèbe O., Cara M. et Cansi Y., 2015: Mw Estimation from Crustal Coda Waves Recorded on Analog Seismograms, BSSA, Vol. 105, No 2A, doi:10.1785/0120140226.

De Rubeis, V., Gasperini, C., Maramai, A., Murru M., et Tertulliani A., (1992). The uncertainty and ambiguity of isoseismal, maps. Earthquake engeneering and Structural Dynamics, Vol 21, 509-523.

De Rubeis et al. (2005) Application of Kriging Technique to Seismic Intensity Data, Bulletin of the Seismological Society of America, Vol. 95, No. 2, pp. 540–548.

Deutsch, C.V. et A.G. Journel. (1992). GSLIB - Geostatistical Software Library. Oxford Univ. Press, New York, 340 p.

Dubrule, O. (1984). Comparing Splines and Kriging. Computers & Geosciences, 10(2-3): 327-33.

Gandin, L.S. (1965). Objective Analysis of Meteorological fields. Israël Program for Scientific Translations, No. 1373, 242 p.

Gasperini P. , G. Vannucci, D. Tripone, E. Boschi (2010) The Location and Sizing of Historical Earthquakes Using the Attenuation of Macroseismic Intensity with Distance, Bulletin of the Seismological Society of America, v. 100 no. 5A p. 2035-2066

Giovanni CARDENAS (Novembre 2004). Utilisation du module « Geostatistical Analyst » d'ARCVIEW dans le cadre de la qualité de l'air. INERIS

Gratton, Y. et C. Lafleur (2001). Le Matlab Kriging Toolbox. Version 4.0. Manuel de référence, INRS-ETE. Le logiciel est disponible gratuitement à l'adresse suivante : http://www.inrs-ete.uquebec.ca/activites/repertoire/yves_gratton/krig.htm

Gratton, Y., L. Prieur, R.G. Ingram, et C. Lafleur. (2002). Les courants en mer d'Alborán Est pendant la campagne Almofront-I. Rapport interne, INRS-ETE.

Journel, A.G. and C.J. Huijbregts. (1978). Mining Geostatistics. Academic Press, 600 p.

Krige, D.G. A statistical approach to some basic mine valuation problems on the Witwatersrand. (1951). J. of Chem., Metal. and Mining Soc. of South Africa, 52, 119-139.

Kunze T (1986) Ausgangsparameter für die Abschätzung der seismischen Gefährdung in Mitteleuropa. Jber Mitt Oberrhein Geol Ver Stgt 68:225–240

Levret, A., Backe, J.C. & Cushing, M., (1994). Atlas of macroseismic maps for French earthquakes with their principal characteristics, Nat. Haz., 10, 19–46.

Liebelt, P.B. (1967). An introduction to Optimal Estimation, Addison-Wesley, 267 p.

Marcotte, D. (1991). Cokriging with MATLAB. Computers & Geosciences, 17(9): 1265-1280.

Maruyama Y. and F. Yamazaki (2006) Relationship between seismic intensity and drivers' reaction in the 2003 Miyagiken-Oki earthquake Structural Eng./Earthquake Eng., JSCE, Vol. 23, No. 1, 69s-74

Matheron, G. (1972). Theorie des variables regionalisees, in Traite d'Informatique Geologique, Masson, Paris, 306–378.

Matheron, G. (1963). Principles of Geostatistics. Economic Geol., 58, 1246-1268.

Manchuel K., D. Baumont, J. Benjumea, M. Cara, M. Denieul, J. Bonnet, C. Durouchou, P. Traversa, E. Nayman (2015). Vers un nouveau catalogue de sismicité pour la France métropolitaine aux échelles historique et instrumentale : contributions du projet SIGMA, extended abstract, colloque AFPS 30/11–02/12 2015, Marne la Vallée, France.

Musson, R. M. W. (2000). Intensity-based seismic risk assessment, Soil, Dyn. Earthquake Eng. 20, 353–360.

Musson R. M. W. and M. J. Jiménez (2008) Macroseismic estimation of earthquake parameters, NERIES project report, Deliverable NA4-D3: Procedures for macroseismic estimation of earthquake parameters, http://emidius.mi.ingv.it/neries_NA4/docs/NA4_D3_v2_2.pdf.

Pasolini C., P. Gasperini D. Albarello, B. Lolli, V. D'Amico (2008) The Attenuation of Seismic Intensity in Italy, Part I: Theoretical and Empirical Backgrounds, Bulletin of the Seismological Society of America, v. 98 no. 2 p. 682-691

Schenková Z., V. Schenk, I. Kalogeras, R. Pichl, P. Kottnauer, C. Papatsimba and G. Panopoulou (2007) Isoseismal maps drawing by the kriging method, Journal of Seismology, Volume 11, Number 1 , 121-129.

Sirovich L., F. Cavallini, F. Pettenati and M. Bobbio (2002) Natural-Neighbor Isoseismals, Bulletin of the Seismological Society of America, v. 92 no. 5 p. 1933-1940

Thywissen K and J. Boatwright (1998) Using safety inspection data to estimate shaking intensity for the 1994 Northridge earthquake, Bulletin of the Seismological Society of America, v. 88 no. 5 p. 1243-1253.

Tselentis G-A. and E. Sokos, (2012) Relationship between isoseismal area and magnitude of historical earthquakes in Greece by a hybrid fuzzy neural network method, Nat. Hazards Earth Syst. Sci., 12, 37–45, doi:10.5194/nhess-12-37-201

Web sites:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/Understanding_interpolation_analysis/009z0000006w000000, ArcGis Resource Center

http://www.franceseisme.fr/donnees/intensites.php

http://www.franceseisme.fr/donnees/BD-MFC/ (BD-MFC: Base de Données Macrosismiques Françaises Contemporaines).

www.sisfrance.net

http://www.seismologie.be/index.php?LANG=FR&CNT=BE&LEVEL=120