Transposing an active fault database into a seismic hazard fault model for nuclear facilities

Part A: Building a database of potentially active faults (BDFA) for metropolitan France

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Abstract

The French Radioprotection and Nuclear Safety Institute (IRSN), with the support of the Ministry of Environment, compiled a database (BDFA) ~~in order~~ to define and characterize known potentially active faults of metropolitan France. The general structure of BDFA is presented in this paper. BDFA ~~contains~~ reports to date ~~a total of~~ 136 faults and represents a first step toward the implementation of seismic source models that would be used for both deterministic and probabilistic seismic hazard calculations. A robustness index was introduced, highlighting that less than 15% of the database is controlled by reasonably complete datasets. An example transposing BDFA into a fault source model for PSHA (Probabilistic Seismic Hazard Analysis) calculation is presented for the Upper Rhine Graben (Eastern France); and exploited in the parent paper (part B) in order to illustrate ongoing challenges for probabilistic fault-based seismic hazard calculations.

1 Introduction

The practice acquired in nuclear regulation over the last decade as well as the feedback arisen from recent earthquake consequences on Nuclear Power Plants (e.g., Kashiwazaki-Kariwa in 2007, Fukushima and North-Anna in 2011), have challenged the expertise of the IRSN (French Radioprotection and Nuclear Safety Institute). Hence, IRSN's researches related to the geological aspects of Seismic Hazard Analysis (SHA) have been focused on 3 principal axes: (1) updating national seismotectonic zoning pattern (Baize et al., 2013); (2) performing and publishing collaborative studies on specific French active faults (cf. Cushing et al. 2008, Baize et al., 2011; Garcia Moreno et al., 2015, De La Taille et al., 2015); and (3) implementing the BDFA (BDFA from the French terms of *Base de Données des Failles Actives* which means Active Faults DataBase) ~~,~~ a database concerning the potentially active faults of ~~the M~~metropolitan France. These issues directly follow key aspects reported in the International recommendations for SHA in Site Evaluation dedicated guides (cf.

~~International Atomic Energy Agency~~IAEA, 2010) where matters linked with both seismic motions and surface faulting are addressed; and in~~meets~~ the requirements of the French deterministic Fundamental Safety Rule (RFS 2001-01, ASN, 2001) for the determination of ground motions at sites~~ as well~~.

The above mentioned third axis started in 2009 and consists in the on-going BDFA project (Palumbo et al., 2013~~); funded by the IRSN and the French Ministry for~~ of the ~~environment~~). It represents a first step to support SHA calculation that needs a collection of geological information in order to characterize seismic sources~~ information~~.

~~This paper introduces the BDFA framework & principles.~~This new database compiles available data on faults with post Late-Miocene activity evidence in metropolitan France, including geometrical properties, kinematics, slip-rates etc. All this information is made available as fault map and related tables for further applications. Currently, the project focuses on faults longer than 10 km (roughly capable of producing M≥6 events according to Wells & Coppersmith, 1994) and crossing a 50-km-circular area having its radius centred on French nuclear facilities (Fig. 1). Future implementations of BDFA should address larger areas of investigation at ~~the entire country ~~scale of the entire country.

BDFA aims at representing a first step towards the constitution of a seismic sources catalogue that can be later used in SHA as well as in PFDHA (Probabilistic Fault Displacement Hazard Analyses) calculations. An outlook of BDFA in the upper Rhine Graben and its transcription into a source model for PSHA calculation is presented in the final part of this paper.

2 Rationale behind BDFA

Despite its distance to active plate boundaries and relatively low to moderate seismotectonic activity (intraplate domain), ~~research activities proved that in metropolitan France ~~both significant earthquakes (e.g. historical catalogue, ~~www.sisfrance.net~~SISFRANCE) and surface faulting (e.g. Sébrier et al., 1997~~,~~; Chardon et al., 2005) have occurred in metropolitan France during the historical and pre-historical times~~have occurred in the past~~.
The starting point for building the BDFA relied~~y~~ on ~~some ~~previous ~~works ~~research~~dealing with similar issues~~, namely ~~;~~: 1) the seismotectonic map released by Grellet et al. (1993) and the active fault database of southeastern France (Terrier, 2004), 2) the IRSN catalogue of faulting evidences affecting Quaternary deposits (Baize et al., 2002), and~~,~~ 3) the French catalogue of neotectonic evidences (available online at www.neopal.net). ~~Those previous works are~~This early work was based upon both a catalogue of published (scientific articles, PhD thesis…) and unpublished reports (technical reports, ~~student works~~master thesis…) as well as an important interpretation phase performed by the authors themselves.
BDFA aims at reflecting as much as possible the available datasets, either for the establishment of fault mapping, or for the description of the~~ir~~ fault activity. Because various opinions may have been proposed by different authors, at different times and at different scales, we ~~have ~~compiled their interpretations/data, in a specific form for each fault complementing the

BDFA traces and tables. Our own choices on fault parameters and associated uncertainties are therefore tracked and referenced to the aforementioned form. These forms ~~are written in French and~~ are ~~available on request as well~~ and thes neotectonic and structural syntheses compiled at regional scales (i.e. Alps, Britany, Jura Mountains…)~~.~~ are written in French and are available upon request.

Among the parameters compiled in the database, we focused on the two following critical points.

Defining the surface fault trace

The main cartographic reference for the BDFA is that of ~~After~~ ~~Fourniguet (1978),~~ Grellet et al. (1993), who following Fourniguet (1978), first attempted to synthetize neotectonic and active faults ~~over~~ across France at the 1:1 000 000 scale~~; hence it is the main cartographic reference of BDFA~~. This fault mapping suffered many simplifications and a rough cartographic representation, so that it cannot be operated at a more precise scale. Our first objective was then to improve this mapping through the analysis of a broad literature including geological and thematic maps at different scales (down to 1:50 000 geological maps), ~~the use of increasingly accurate~~ Digital Elevation Models, ~~availability of~~ aerial photographs when available and specific publications containing maps at various scales. BDFA ~~was~~ is developed under a GIS structure in which ~~,~~the basic unit is the fault segment, coupled with a relevance index describing the status of knowledge concerning its cartographic trace (reliable, uncertain, hidden, and suspect). Faults may be defined from a single segment or a set of segments forming a discontinuous trace at the surface. ~~considering four degrees of uncertainty (reliable, uncertain, hidden, and suspect) to reflect the status of knowledge of each segment.~~ The fault segments traces are paired with explicit tables~~; therefore, fault segments are coupled with several data~~ reporting the data gathered in the literature and tracing as much as possible the consulted sources.~~whose original sources can be traced.~~

Discriminating whether a fault is considered active or not

This task represents a key point of the database, however, not straightforward to determine, because of both ~~technical~~ scientific and regulatory~~ion (against what do we want to protect themselves?) purposes~~issues.

From a ~~technical~~ scientific point of view, when no sign of current activity is recorded along a fault (~~from s~~from seismicity and ~~,~~ geodesy~~tic measurements~~), which is often the case in intraplate domains, determining whether a fault is active or not is based upon the age of the youngest observed deformation, with particular attention to multiple movements occurring~~ed~~ over the last thousands to hundreds of thousands of years.~~.~~ ~~The bottom line being that the younger the deformation is, the more likely it will generate earthquakes in the future. Hence, discerning which segment is active or not will be based upon a temporal threshold.~~

From a ~~political~~ regulatory point of view, national and international definitions of when a fault should be considered active may differ when it comes to deciding on ~~in defining~~the temporal limits ~~to be~~that should be ~~-~~taken into account~~ to define active faulting and related ground motions~~. Concerning the determination of ground motion at sites, the French ~~ASN~~

~~(~~Nuclear Safety Authority~~)~~ rule (ASN, 2001)~~RFS 2001-01)~~ ~~stipulate~~ recommends for example that the hazard related ~~ground motion associated if ato~~ an active fault ~~paleo-earthquake~~ should be taken into account ~~along a fault~~ in defining the ground motion related to a potential event whose return period ~~is evidenced along a fault, then the ground motion associated to an event whose~~ when the ~~return time period of the paleo-earthquake would~~ is on the order of~~be~~ a few tens of thousands of years ~~should be taken into account along this fault~~. Concerning the fault displacement hazard, the ~~I~~international nuclear safety guideline~~s~~ (IAEA, 2010) indicates that for intraplate domains fault capability (i.e. capacity of a fault to rupture the surface during an earthquake) should be assessed by collecting geological information~~'~~s ~~through~~ covering the Plio-Quaternary ~~time span~~period ~~for intraplate domains~~ (the temporal threshold to account for should then be 5.3 Myr). ~~It~~ This time span is ~~in comparison~~ significantly larger than the one proposed by the US Nuclear Regulatory Commission (US-NRC, 2017) which advises to set this limit at 35 kyr for faults that ruptured once at or near the surface or 0.5 Myr for faults highlighting recurring earthquakes.

~~In~~ At the metropolitan France scale, the orientation of the tectonic stress field has not experienced dramatic changes since the end of Miocene, with the persistence of the convergence between Africa and Eurasia. ~~(Baize et al., 2013).~~ In parallel, the age of Plio-Quaternary sediments that may attest for ~~active faulting~~deformation along faults are often absent or poorly constrained. In this context, we considered reactivations of past structures as possible and build the BDFA as a potentially active fault database, thus including late Miocene to Quaternary structures as considered in previous compilation by Baize et al. (2013) (Figure 1).

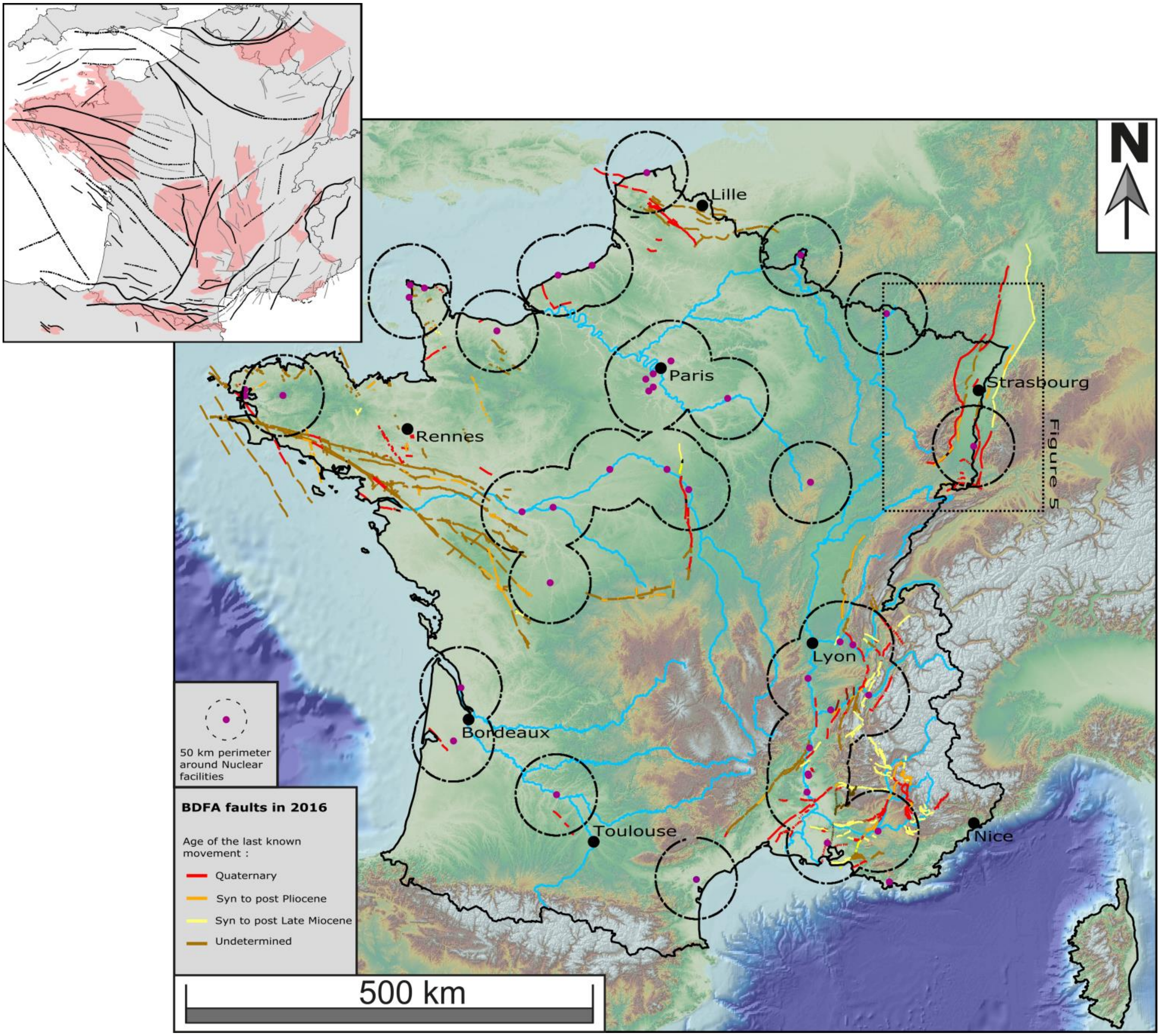


Figure 1: Map of BDFA (Google ~~e~~Earth kml file provided in ~~annexes~~supplementary materials) at the scale of metropolitan France. Faults coloured by the age of the last known movements. Black circles represent a 50 km perimeter around each nuclear facility. The black dashed rectangle represents the geographical imprint of figure 5. In top left, simplified structural sketch of France (modified from Baize et al., 2013): crystalline basement outcrops are defined in light red; major basement faults in black and minor faults in grey.

3 The Database structure & statistics

The database structure (see ~~Annexes~~supplementary materials) was inspired by other databases~~,~~ developed in the world, such as the ones from ~~as~~ the USA (QFAULT~~,~~; Haller et al., 2004), New-Zealand (NZAFD~~,~~; Langridge et al., 2016), Japan (Active fault database of Japan; AIST 2016~~from the geological survey of Japan~~), Italy (ITHACA; Michetti et al., 2000) or Iberia (QAFI~~,~~; García-Mayordomo et al., 2012). The proposed map for metropolitan France is associated with a relational database describing the state of knowledge for each fault segment. This database is composed of several thematic tables (designed in Microsoft Excel spreadsheets) linked together with an identification key.

The identification key for each fault ~~system~~ described in BDFA (ID_Fault - IDF) corresponds to the one referenced in the French Geological survey (BRGM) fault database related to the 1:1 000 000 geological map. A new identification key ~~has been produced to~~ give a unique reference to each fault segment (ID_UNIQUE - UID). These two identification keys allow to link together the following tables:

- The MAIN TABLE contains all gathered fault parameters with associated uncertainties when available (i.e. map characteristics, geometry, neotectonics, ages and kinematics, calculation of a robustness index, editing notes and release date);
- The “INDEX-REF” & “REFERENCES” tables list the publications used to characterize the ~~active~~ faults~~ system~~;
- The “INDEX-EVIDENCES” table includes all neotectonic evidences reported in the NEOPAL and IRSN databases (respectively ~~www.neopal.net~~NEOPAL and Baize et al., 2002);
- The “INDEX-SEISMIC” reports largest earthquakes, essentially events described in the historical archives (~~www.sisfrance.net~~SISFRANCE) for which magnitude values are proposed by Baumont and Scotti (2011);

All fields are ~~explained~~ described in the BDFA-table enclosed in ~~annexes~~the supplementary materials. Most of them are manually implemented, while we took advantage of GIS capabilities to implement cartographic parameters such as length, azimuth, tips coordinates. When a field can’t be informed because of lacking data, a numerical code of *99* is attributed for numerical fields and an *UnDef* code is attributed for text fields.

3.1 Fault traces and segmentation

Fault segmentation and location are key parameters in seismic hazard assessment (Wesnousky, 1986~~,~~;~~Biasi & Wesnousky, 2016,~~ Field et al., 2015; Biasi & Wesnousky, 2016). ~~When~~ While building-up the ~~french~~~~French~~ BDFA, we basically ~~gave priority~~mapped ~~to the published~~ fault traces and associated segmentations directly as they were defined in the literature. Where several references were available for a single fault or fault segment, we decided to report the traces proposed from the most recent or reliable references. These principles have largely been applied for faults in eastern, northern and southern France, because most of them have ~~long~~ been studied ~~through~~for many years. However, the age of some publications led us to precise the mapping in the light of more recent cartographic documents (see the 2nd point below).

~~However~~In parallel, few active or potentially active faults have been studied ~~–~~in detail in central, and north-eastern France~~France~~. It may also happen, in particular for long faults (e.g.~~:~~ the south Armorican shear zone is longer than 500 km), that only one or a few segments of a fault have been studied because of the occurrence of a particular local seismic crisis or ~~,~~ the exposure of ~~a~~ local neotectonic evidences. Consequently, precise mapping are often missing or not reliable due to coarse drawings. In this context, ~~W~~we ~~therefore proposed~~complemented the available fault traces with~~, when the available data cannot be considered as reliable,~~ a new mapping including fault segmentation based on the following ~~as following~~:

- As defined earlier, the basic unit filled in the database is the fault segment (UID), grouped into a fault (~~–~~IDF), forming a discontinuous trace at the surface,
- In order to propose a surficial trace of the fault segments, we relied on the available map documents with a cartographic scaled approach. Priority was given ~~at~~to large scales geological maps form the French geological survey (1:50 000) and then, if not available, ~~at~~to lower scales maps (1:250 000 & 1:1 000 000). As a last resort, Digital Elevation Models (DEM) and derived slope maps, as well as air photos, were analysed to propose fault segment~~s~~ traces based on their topographic signature. Finally, each proposed fault segment trace goes along with a reliability index (TRA: reliable, uncertain, hidden, or suspect). This reliability index was also adopted to qualify all faults segments of the database,
- ~~Regarding the definition of the surface trace of the fault, priority was given at available large scales geological maps (1:50 000) and then, if not available, at lower scales maps (1:250 000 & 1:1 000 000). As a last resort, Digital Elevation Models (DEM) and derived slope maps, as well as air photos, were analysed to propose fault traces based on their topographic signature. Finally, each proposed fault trace goes along with a reliability index (TRA: reliable, uncertain, hidden, or suspect),~~
- ~~The basic unit is the (fault) segment. Segments are grouped into a (fault) system or (fault) family. A fault system is composed of segments having similar characteristics (notably their direction) and forming a discontinuous trace at surface,~~
- Fault segments were ~~generally~~ archived into 4 ~~families~~ typologies (Major~~,~~=M; Parallel~~,~~=P; Oblique~~,~~ =OB and Orthogonal~~,~~ =OX). This term was introduced ~~in order to be able~~ to differentiate what is considered to be the main fault trace (Major) from satellite or conjugate systems. This is especially useful for inherited faults in hard rocks (e.g. Armorican shear zones) for which geologists have mapped all brittle structures and where it is not possible to reject the potentiality of faulting due to the activation of the main structure. This distinction accounts for the relative strike of the subordinate segments with respect to the major fault trace (M): between 0-15° = P; between 16~~5~~ and 70 ° = OB, between 71~~-~~° and 90~~-~~° = OX (Figure 2),

- The unique identification number (UID) of each fault segment is obtained by concatenating IDF, the segment typology (M, P, OB, OX) and the number of the segment (SNB). As an example (Table 1), the 2^{nd} major segment of the Vuache fault (IDF=5317) will be quoted 5317_2_M.~~,~~
- ~~Fault segments smaller than 5km are gathered to their neighborest segment when they present a similar strike,~~
- ~~Two fault segments presenting a similar direction have to be gathered if their tips are at a distance less than 1km,~~
- ~~A fault that presents a rather small (<15°) or regular change in direction is not segmented; conversely, when linear faults present direction changes higher than 15°, the fault is segmented.~~

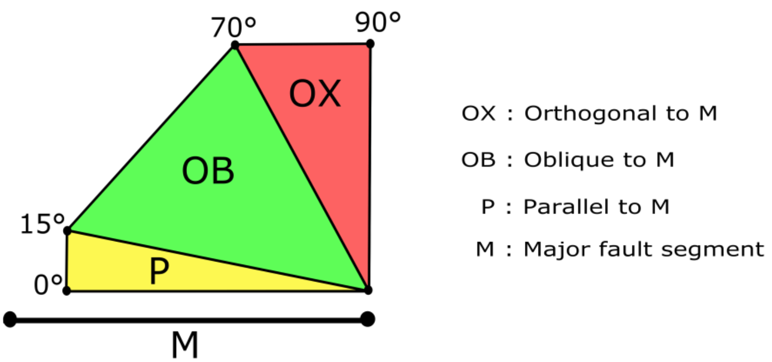


Figure 2: Segmentation typologies (TYP) used to define the identity code of each segment (UID).

In any case, whether the retained geometries derive from publications or maps, fault segments are always defined on the basis of static geologic criteria or at least long term morphological evidences of deformations. This is mainly due to the fact that, in metropolitan France, dynamic criteria (surface ruptures, fault source models etc.) cannot be derived from the analyses of major earthquakes, the last surface-rupturing event being probably the Lambesc earthquake, in 1909 (Chardon et al., 2005).

~~Finally, we assign a unique identification number (ID-UNIQUE) to each fault segment. This identification number is obtained by concatenating the ID_FAULT, the segment family (M, P, OB, OX) and the number of the segment.~~

3.2 Age of deformations ~~&~~and slip-rates

The age of the youngest deformed geological horizon ~~is also a key parameter because it~~ will condition~~s~~ whether the causative fault/fault segment is considered in hazard calculation or not (French RFS 2001-01;~~,~~ IAEA SSG-9, 2009~~,~~; US-NRC 10CFR part 100, 2017). In a second time, once a fault or a fault segment is considered, the associated slip-rate will be the most influencing parameter in quantifying its seismogenic activity.~~A good constraint on the age of the most recent deformations allows, when a total amount of slip can be determined over the period considered, to calculate a fault slip rate~~ Consequently, we designed the database ~~in order to be able~~ to provide the necessary parameters to (1) assess the age of the last movement along a fault or fault segment, and (2) calculate slip-rates or understand how they were derived. Concerning the age of the last movement, w~~W~~e defined the following parameters to be filled in the database for each fault segment: ~~(Figure 2):, but they are rarely reported in the original consulted documents. Even the published slip rates values were systematically controlled before integration into the database, because of sometimes ambiguous, vague or inconsistent information in terms of chronology and stratigraphy. Conversely, in case no slip rate are given by authors but good constraints are provided in terms of chronology and amount of slip, we propose a slip rate based on their observations.~~

~~We defined the following parameters to be filled in the database (Figure 2):~~

~~DCHR: Deformed CHronostratigraphic Unit. Local terminology indicating the most recent chronostratigraphic units involved by faultin~~

- DCHR (Deformed CHRonostratigraphic unit). This field indicates the local terminology of the most recent chronostratigraphic unit involved ~~by~~in faulting~~,~~. These may refer to epochs (e.g. Pliocene, Quaternary…) or to more precise stages (e.g. Riss, Würm…) due to the fact that ~~Because~~ Plio-Quaternary deposits are often ~~badly~~poorly dated, ~~it may cover a wide variety of terms, from epochs (e.g. Pliocene, Quaternary…) to more precise stages (e.g. Riss, Würm…).~~ Depending on the age defined in DCHR, a generic field called Neotectonic Age (NA) is provided in addition and used for mapping. Four predefined terms were adopted to fill the NA field: Quaternary, Pliocene (i.e syn to post Pliocene), Miocene (i.e syn to post Late Miocene), and Undetermined. As a consequence, it may happen, because of ~~lacking~~missing sediments or datings along specific fault segments, that different ages are attributed to segments of a single fault. In this case, it is up to the user to decide whether the considered fault is active or not,~~,~~
- DCHRT and DCHRB (DCHR Top and Base, in years)~~: age DCHR Top.~~ . These fields inform the numerical age of the top and the base of the youngest unit (DCHR) involved ~~by~~in the faulting.~~Numerical value which gives the upper limit (geochronological) of the unit involved in the deformation~~ It may happen that one, both or none of these ages are available,
- DM (Dating Method). It refers to the dating method used to establish DCHRT and DCHRB. We ~~introduced~~rely on three predefined terms: 1) *radiometric* when ~~absolute~~numerical ages are available, 2) *relative* when ~~based on~~ages of movement can be constrained by stratigraphic or biostratigraphic ~~relationships~~information~~,~~ and 3)~~-~~*indirect* when only *facieès* ~~based~~ correlations are available at regional scales,

- NWEU (North West Eu~~U~~ropean chronostratigraphic stages)~~:~~. Because the terminology of Quaternary glaciations used over time in the French bibliography often refers to Alpine regional~~s~~ stages, we introduced a field referring to their corresponding north-werstern European stages~~Terminology indicating the most recent North West European Chronostratigraphic units which is involved by fault. If for example in literature is reported Würm, it will report Weichselian~~,
- UCHR (~~:~~ Undeformed CH~~r~~Ronostratigraphic ~~U~~unit). This field indicates the ~~L~~local terminology of the ~~indicating the most recent~~oldest chronostratigraphic units not involved ~~by~~ in the faulting. As mentioned previously, ~~for~~ DCHR~~, it~~ may cover a wide variety of terms,~~,~~

- ~~DCHRB (in years): age DCHR Base. Numerical value which gives the lower limit (geochronological) of the younger unit involved in the deformation. If dating doesn't exist, it could be esteemed through chronostratigraphic correspondent,~~
- ~~DM: Dating Method used to establish DCHRT and DCHRB; 3 predefined terms: radiometric, relative (stratigraphic principles, biostratigraphy), indirect (facies),~~
- ~~OST (in years): Offset Span Time. Time span representing the value used for calculate slip (rate),~~

  ~~AR: Age of the chronostratigraphic Units used for determining slip Rates (restraining OST).~~

Concerning slip rates, we were rarely able to extract from the consulted references direct information~~'s~~ concerning fault slip rates~~ from the consulted references~~. Published slip rates values were controlled before integration into the database, when ~~because~~ chronological and/or stratigraphical issues arose because of ~~of sometimes~~either ambiguous, or vague or even inconsistent information~~ in terms of chronology and stratigraphy~~. ~~In addition,~~When reliable~~ good~~ constraints in terms of chronology and amount of slip can ~~sometime~~ be extracted from the consulted references (scientific papers, maps, etc.~~…~~), then ~~. In this case, w~~we propose slip-rates based on these observations. The following parameters are filled in the database:~~Even the published slip rates values were systematically controlled before integration into the database, because of sometimes ambiguous, vague or inconsistent information in terms of chronology and stratigraphy. Conversely, in case no slip rate are given by authors but good constraints are provided in terms of chronology and amount of slip, we propose a slip rate based on their observations.~~

- NEOF (NEotectonic OFfset). It informs the minimum and maximum offset values of the marker used to estimate slip-rates and associated uncertainties. In general, it corresponds to the amount of slip registered by the youngest available dated and faulted marker,
- OST (Offset Span Time, in years). It reports the time span used to calculate slip-rates. It could be either a single value or a bracket depending on the presence or absence of dated deformation markers,
- AR (Age used for Rate). It mentions the Name of the chronostratigraphic Units constraining OST. It may happen that OST doesn't correspond to DCHR because the amount of slip (i.e. NEOF) in the youngest affected sediments

can’t be quantified. In this case, longer term slip rates may be derived from older stratigraphic/morphologic markers.

Slip-rates ranges are finally calculated by dividing NEOF with OST. When sufficient data are available, it may be decomposed in Vertical Slip-Rate (VSR) and/or Horizontal Slip-Rate (HSR).

In figure 3, we illustrate a theoretical case in which we reported the different fields informed in the database. ~~It~~This corresponds to an ideal case where stratigraphic markers with absolute ages are available within the youngest deformed unit, which will allow recovering a range of slip-rates related to the most recent deformed horizon.

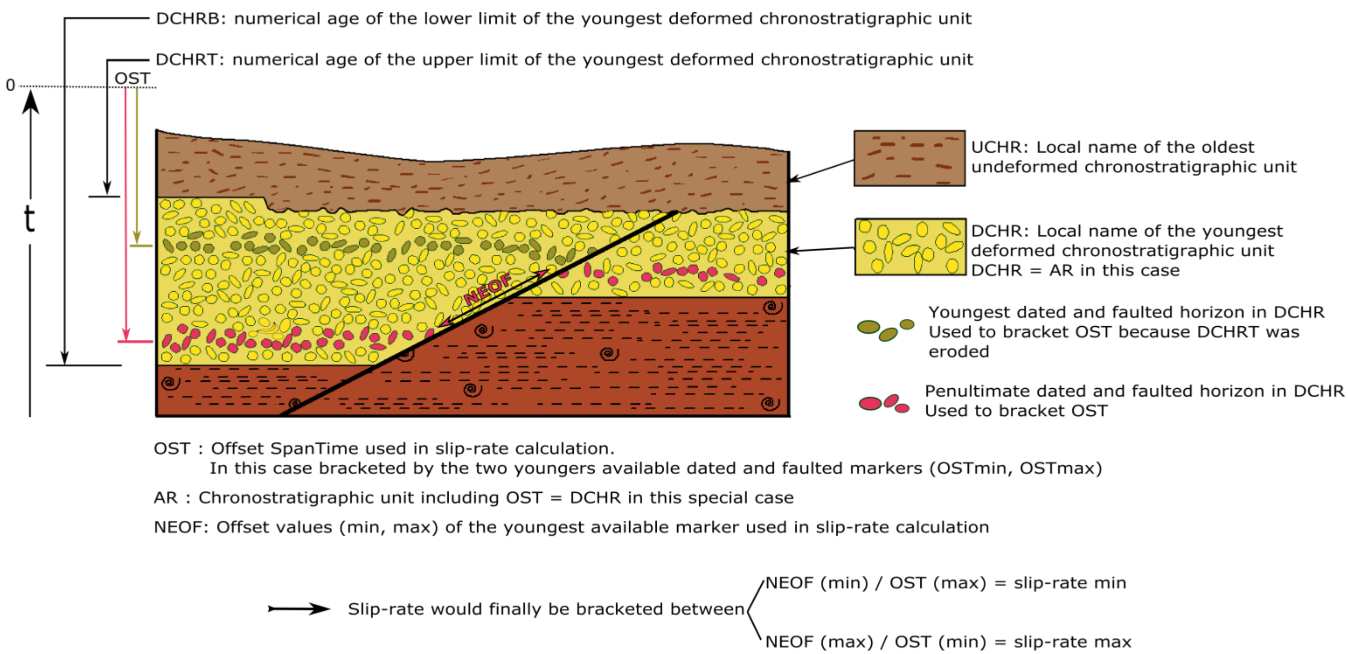


Figure ~~2~~3: Conceptual example illustrating the different chronological terms used in BDFA ~~Stratigraphic relationships considered~~ to determine the age of deformations and slip-rates.

A real example illustrating the use of long term slip-rates because of ~~lacking~~missing quantified tectonic offsets in the most recent formations is given for the Vuache fault and derived from the publication of Baize et al., 2011.

The parameters introduced in the database for the 5317_2_M segment are reported in table 1. Along this fault segment, faulted Quaternary deposits were observed in a quarry and dated at the end of Riss (≈139 kyr) through OSL techniques. Authors were unfortunately not able to quantify the deformation in these sediments. In order to define a long term fault slip-rate, they focused on a well-marked morphological shift of 2 km of the Mandallaz anticline, related to the formation of the Jura Mountains, which started during Miocene (between the onset of Serravalian and the end of Tortonian). Assuming a constant deformation rate since Miocene, they came ~~out~~estimated~~ with~~ a 0.15 to 0.28 mm/yr slip-rate that is reported in the database.

BDFA fields	*Parameters in BDFA*	*Comments*
UID	***5317_2_M***	***Vuache fault Balme de Sillingy segment***
DCHR	***End of Riss***	***Deformed Rissian deposits, observed in a Quarry.***
DCHRT	***99***	***Top of deposits are lacking***
DCHRB	***139 kyr***	***Result from OSL dating is 139 ± 16 kyr***
DM	***Radiometric***	***OSL dates***
NWEU	***Eemian-Saalian***	***-***
UCHR	***UnDef***	***No overlying sediments***
NEOF	***2000 m***	***Morphological shift of the Mandallaz anticline***
OST	***13,6 Myr – 7,2 Myr***	***Base of Serravalian – Top of Tortonian***
AR	***Miocene***	***Deformation in Jura Mts starts in between Base of Serravalian and Top of Tortonian***
Slip-rate	***0,15 – 0,28 mm/yr***	***Horizontal slip-rate***

Table 1 : BDFA parameters concerning the 5317_2_M segment of the Vuache fault. Data derived from Baize et al., (2011)

3.3 Robustness index

The current version of the database includes 136 faults with a total of 581 fault segments. Among these 581 segments, 118 are ~~qualified~~ reported as active during the Quaternary. We provide a “robustness index” (RI), estimated for each segment. This index aims at providing a ranking of the fault population in terms of reliability of their potential activity ~~reliability~~. RI *(Eq.1)* follows the empirical expression modified from Baize et al.~~,~~ (~~2013~~2012):

$(\boldsymbol{Eq.1})\ IR = (TI + \mathbf{0.1}) * (TI + IAN + GI + \mathbf{3}HIST + \mathbf{4}INST + \mathbf{2}GDR)$ ~~**RI = (S + 0.1) x (S + Age + M + 3H + 4I + 2G)**~~

Where:

- ~~S~~TI: Trace index (Structural knowledge). It may be valued 0 or 1, according to unknown or well-known ~~or unknown~~ tectonic structures, respectively (cf. field TRA in the BDFA tables)~~,~~
- IAN: Age index (~~:~~ time of last recognized displacement)~~.~~ Derive from the NA field, it may be valued 1, 2, or 3 for ~~Paleogene~~Miocene, Pliocene~~Neogene~~, and Quaternary, respectively~~,~~; and 0 for undefined/presumably post Paleogene,
- ~~M~~GI: Geo~~M~~morphological index (morphological expression of the fault). It may be valued 0 or 1 depending on~~,~~ ~~according to~~ negligible or prominent surficial expression, respectively,
- HIST: it questions if historical seismicity could be associated with the segment fault trace~~historical seismicity parameters~~. It may be valued 0 or 1. The value 1 is adopted when a significant historical earthquake (epicentral

intensity ≥ V, according to ~~www.sisfrance.net~~SISFRANCE, which for this intensity level may be considered complete since the middle of the 19th century according to Bonnet et al., 2014) occurred ~~inside an area widening~~within 5 km from~~of~~ the fault trace,

- INST: it questions if instrumental seismicity could be associated with the segment fault trace~~instrumental seismicity parameters~~. It may be valued 0 or 1. The value 1 is adopted when significant instrumental activity (either significant earthquakes with Ml ≥ 4 or swarms/alignments of low magnitude events) occurred ~~inside an area widening~~within 5 km ~~of~~ from the fault trace,
- GDR: geodetical data indicating displacement between the two sides of the fault~~along the fault~~. It may be valued 0 in case of lacking data or 1 if the fault is actually experiencing active deformations~~, according to lack or recognised movement, respectively~~.

This index is subjective by nature. It gives a higher weight to "dynamic" criteria like seismicity, because we consider that it is the most relevant criterion to prove seismotectonic activity. The total population of the database was classified within equally-separated RI classes (Figure 3). It highlights that a relatively small part of BDFA fault segments are reliably potentially active (82 segments with an RI > 10, corresponding to 42 faults over 136 or ≈15% of the database) and may then help pointing out the need~~s~~ for future data acquisitions.

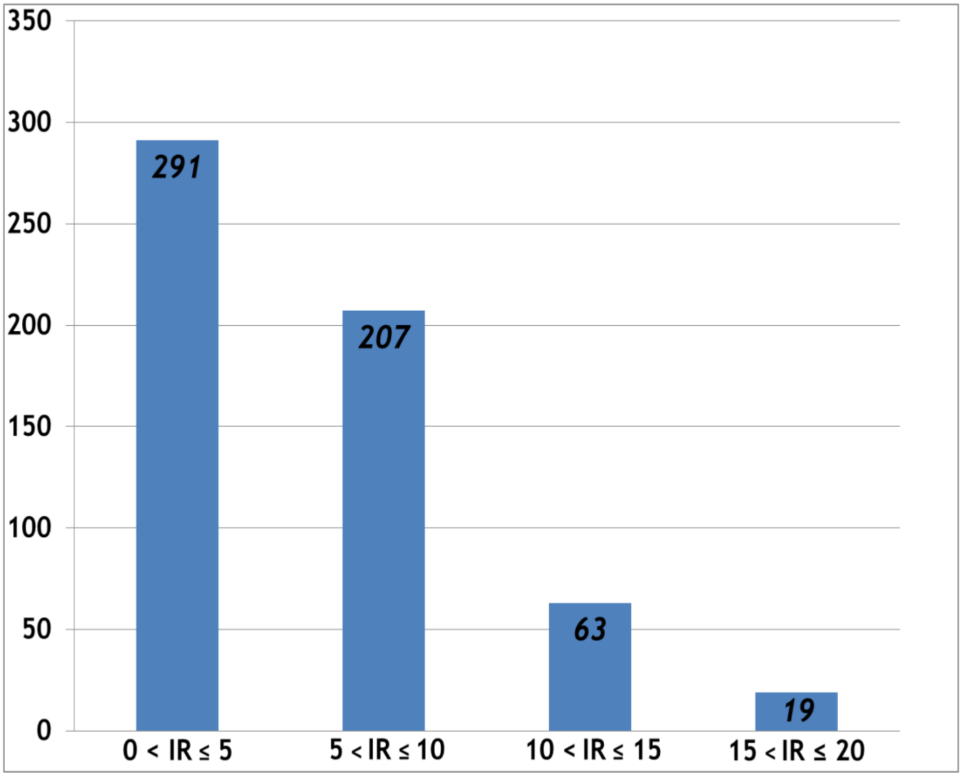


Figure ~~3~~4: Robustness index (RI) distribution for all fault segments described in BDFA.

4 Transposing BDFA into a fault seismic source model for SHA, an exercise in eastern France

The southern part of the Upper Rhine Graben (URG) straddles ~~ing~~ the border between France and Germany from northern Switzerland to Mainz ~~north to Mainz~~ in Western Germany. It~~,~~ presents a significant seismic activity for an intraplate area ~~(Bonjer et al., 1984, Barth et al., 2015)~~with, for instance, ~~. A~~a magnitude 4 or greater earthquake shaking~~es~~ the area~~URG~~ every ≈10 years (Bonjer et al., 1984; Barth et al., 2015). ~~and i~~In 1356, a magnitude ≈6.5 struck the city of Basel in its southernmost part (Lambert et al., 2005). This event is the largest regional earthquake that is ~~registered~~ listed in the Swiss, German and French archives. Macroseismic intensities, based on reported damages, reached VIII-IX in the epicentral area according to the French macroseismic catalog (SISFRANCE). No historical information about a surface faulting is recorded in the ~~manuscripts~~ archives and the fault source of this earthquake is still debated.

Previous investigations have supported the hypotheses that the 1356 historical earthquake might be due either to the activity of West trending buried faults (e.g. Meyer et al., 1994), or to a North trending Rhenish structure (e.g. Meghraoui et al., 2001). Nivière et al. (2008) investigated the north-south ~~NS~~ "rhenish" structures (e.g. Rhine River Fault, see figure 4) and concluded from morphological and borehole data~~evidences~~ that these structures are potentially able to generate earthquakes as ~~strong~~ large as M=6.6-6.8, ~~(~~in the magnitude range of the 1356 Basel earthquake, ~~)~~ in a time frame of several tens of thousands of years.

Because of their ~~closeness~~ proximity to the French nuclear power plant (NPP) of Fessenheim (<10 km), these potential active faults might ~~be hazardous~~pose a hazard ~~on for~~to ~~the NPP~~its safety. In order to perform an exercise aimed at assessing the fault parameters that influence most the results of PSHA calculations at short distance from a site (developed in Chartier et al., this volume), we ~~We hereafter~~ propose as a first step to ~~implement~~~~derive~~construct a fault source model ~~from~~ based on the BDFA, ~~in order to feed an exercise which goal is to assess the fault parameters that influence most the results of PSHA calculations at short distance from a site (developed in the parent paper).~~

~~In the BDFA, the~~The three ~~faults~~ closest-to-NPP faults mapped in BDFA ~~to the NPP~~ are the West Rhenish, the Rhine River and the Black Forest Faults ("faille Rhénane Ouest", "F~~F~~faille du Rhin" and "faille de la ~~"~~Forêt Noire" in BDFA respectively). Only their closest segments to the NPP are considered here (F~~f~~igure 4) and used in the PSHA exercises (see ~~parent paper~~Chartier et al., this volume~~part B~~). Our knowledge about the considered fault segments activity is ~~highlighted~~ summarized by Robustness Indexes varying from RI=4.4 up to RI=15.4 (Figure 4), variation mostly dependent ~~here~~ on the presence or~~/~~ absence of spatially captured ~~historical/instrumental~~ seismicity. However, for the purpose of the PSHA exercise performed in the parent paper, the Reliability Index has not been ~~exploited~~ considered to weigh~~t~~ the activity of the fault segments. In addition, we assume that the static geologic discontinuities used to define the considered fault segments correspond to earthquake segment boundaries. In other words, we didn't consider the possibility of multiple segment rupture scenarios in the PSHA exercise, which must be tested in future calculations. The table in figure 4c summarizes how the BDFA parameters were considered for PSHA calculations:

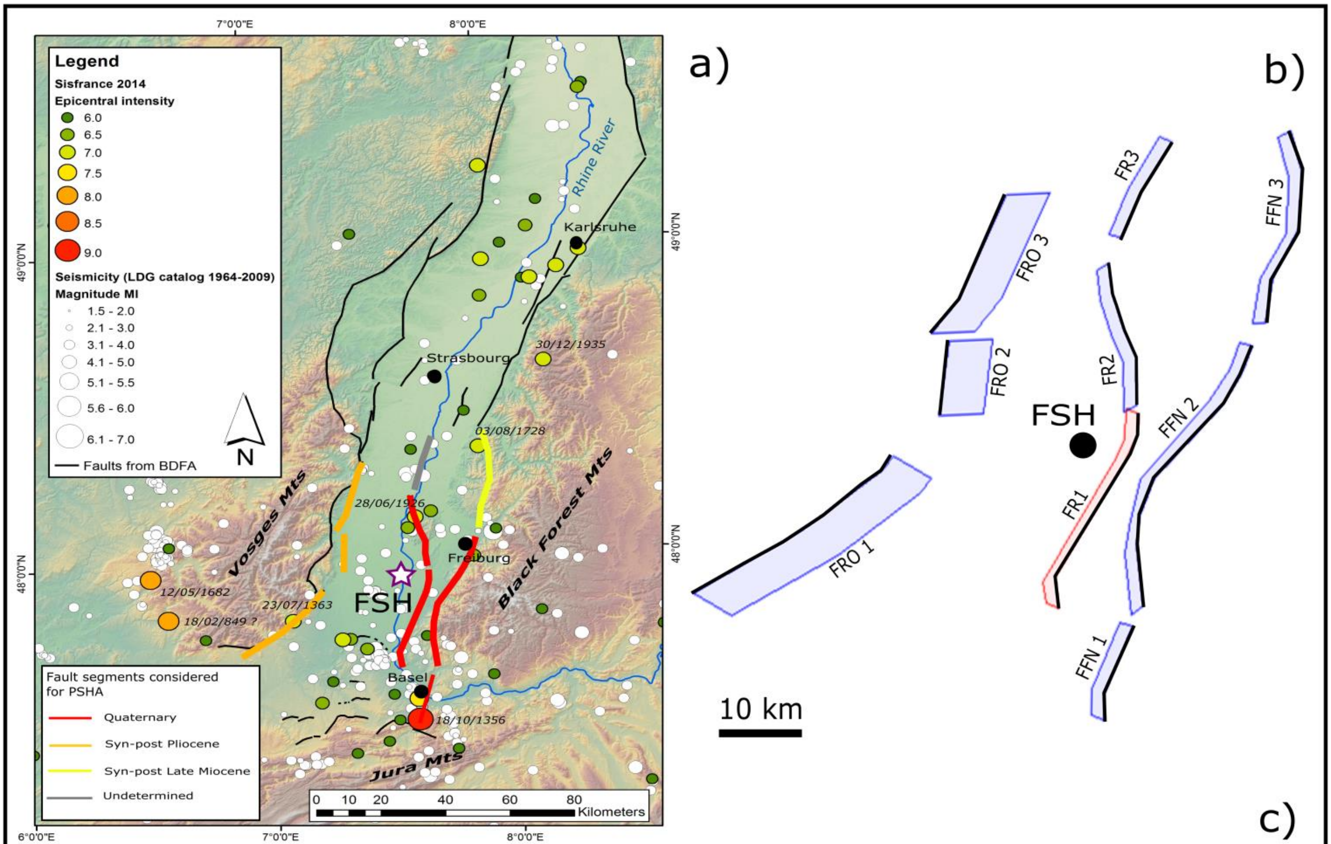
- Faults lengths: BDFA surficial traces ~~were~~ are taken into account and digitized in PSHA CRISIS ~~software V1.2~~2014 (Ordaz et al., 2014 - Figure 4). Lengths may slightly differ due to a rough digitization in the PSHA software. In BDFA, surficial fault traces (figure 4c) of the three considered fault~~ systems~~s were directly derived from the literature,
- Faults depths: in BDFA, we gave ~~gives~~ priority to faults depths characterized through geophysical prospections. Concerning the West Rhenish fault for example, segments' depths in BDFA are derived from the interpretation of reprocessed high resolution industrial seismic profiles published by Rotstein & Schaming (2008). For the PSHA fault source model, we retain depths derived from the analysis of regional seismicity ~~at depth~~ (Edel et al., 2006) and the interpretation of a crustal scale seismic profile (DEKORP-ECORS, Brun et al., 1991). Two depth values will be tested for PSHA calculations: 15 and 20 km,
- Faults dips: we mainly ~~keep~~ relied on the BDFA values, except for the Black Forest fault~~,~~ for which~~where~~ a higher angle~~,~~ equal to the Rhine River fault was ~~assigned~~ preferred (70±10°), in line with what ~~as~~ is proposed in Nivière et

al. (2008). The hypothesis that these faults are structurally related, as proposed by Behrmann et al., (2003) and Rotstein et al., (2005) from reprocessed seismic data, should be tested in future studies, ~~This is due to the fact that dip values in BDFA (50±10°) are derived from very surficial geophysical data (Rotstein & Schaming, 2008), posing geometrical problems at depths with the neighboring Rhine River fault (Rhine River and Black Forest faults will crosscut themselves at depth taking into account dip values from BDFA and considering depths of 15 and 20km),~~

- Faults slip-rates: we considered slip-rates contained in the BDFA (lower and upper bounds). For the Rhine River and the Black Forest faults, slip-rates are available in the literature for only one segment of each fault~~ system~~; we then attributed coherent values to all segments for which no value ~~has been~~were proposed in the literature. Slip-rates along these fault segments were deduced from the analysis of post-Pliocene geological markers (Nivière et al., 2008). For the West Rhenish Fault, considered in BDFA as active during the Pliocene and possibly during Quaternary, no slip rates were found in the literature. We then attribute~~d~~ for this model an upper bound of slip-rate equal to the lower slip-rate determined for both the Rhine River and Black Forest faults; and a lower bound of slip rate coherent with lower fault-slip rates determined in the Lower Rhine Graben following Vanneste et al. (~~,~~ 2013).

It is ~~worth mentioning~~important to mention that in this part of the Rhine Graben, all fault slip-rates that are available in the literature are given as vertical slip-rates, considering that the long-term normal activity observed along these faults is representative of the ongoing deformation processes.~~, leading us to assume a normal faulting kinematic for the considered fault.~~ However, data from seismicity (Edel et al., 2006), geodesy (Tesauro et al., 2005) as well as long term regional stresses (Rotstein and Schaming, 2011) suggest a possible strike slip component along faults in the Fessenheim area. To date, ~~F~~field data ~~to confirm and quantify this strike slip component (possibly dominant)~~ along faults are missing ~~today~~ to confirm and quantify this strike slip component (possibly dominant), but it is clear that such ~~an~~an hypothesis should be explored ~~for~~ in future hazard assessments.

This exercise of ~~translating~~ converting the database into a fault source model shows that this transcription is not straightforward. Concerning the area we considered for this exercise, which is among the most studied in France, only 5 segments over nine present robustness indexes over 10, which means that the basic data we need to build a fault source model ~~may~~is either missing ~~be lacking or being of~~or is of very poor ~~insufficient~~ quality. In this light, even if ~~the database~~ BDFA has been designed to integrate parameters required to implement ~~for the construction of a PSHA~~ a fault source model for PSHA, ~~its transcription is not straightforward and~~ it is ~~then~~ still necessary to make assumptions and account for alternatives when it comes to filling the model parameters~~ data are either lacking, not consistent with each other, or of insufficient quality~~.



Fault_Name	Segment_Name	*Segment name PSHA*	Dip (°)	± Dip	Dip PSHA	Depth (km)	± Depth	*Depth PSHA*	Length (km)	*Length PSHA*	Neotectonic_Age	slip rate (mm/yr)	*Slip rate PSHA*	Robustness (IR)	Bibliography for BDFA
Rhine River Fault	FRR-1	*FR1*	65 W	15	70 ± 10	15	5	*15 to 20*	35	*36*	Quaternary	UnDef	*0,04 to 0,1*	15.4	Segmentation & geometry (Rotstein et al., 2005 ; Nivière et al., 2008 ; Behrmann et al., 2003) - Slip rate (Nivière et al., 2008)
	FRR-2	*FR2*	65 W	15	70 ± 10	15	5	*15 to 20*	25	*27*	Quaternary	0,04 - 0,09	*0,04 to 0,1*	11	
	FRR-3	*FR3*	70 W	99	70 ± 10	15	5	*15 to 20*	20	*20*	Undetermined	< 0,1	*0,04 to 0,1*	4.4	
West Rhenish Fault	Belfort-Guebwiller	*FR01*	50 E	99	50 ± 10	3.5	99	*15 to 20*	36	*36*	Pliocene	UnDef	*0,01 to 0,05*	14.3	Segmentation & geometry (Rotstein et Schaming., 2008, Ford et al., 2007, Bertrand, 2005) - Slip rate (Nivière et al., 2008 ; Cornu et Bertrand 2005)
	Guebwiller-Colmar	*FR02*	55 E	99	50 ± 10	2.5	99	*15 to 20*	16	*16*	Pliocene	UnDef	*0,01 to 0,05*	6.6	
	Colmar-Sélestat	*FR03*	60 E	99	50 ± 10	1.5	99	*15 to 20*	27	*27*	Pliocene	UnDef	*0,01 to 0,05*	6.6	
Black Forest Fault	FFN-1	*FFN1*	40 W	99	70 ± 10	15	5	*15 to 20*	20	*15*	Quaternary	UnDef	*0,05 to 0,15*	11	Segmentation & geometry (Behrmann et al., 2003 ; Nivière et al., 2008) - Slip rate (Nivière et al., 2008)
	FFN-2	*FFN2*	50 W	99	70 ± 10	15	5	*15 to 20*	50	*50*	Quaternary	0,07 - 0,18	*0,05 to 0,15*	11	
	FFN-3	*FFN3*	40 W	99	70 ± 10	15	5	*15 to 20*	35	*35*	Miocene	UnDef	*0,05 to 0,15*	8.8	

Figure 54: a) Potentially active faults from BDFA (in black), selected segments for PSHA calculation in colour (depending on the age of the last movement on the fault). b) Fault source model ~~Fault model~~ as produced for PSHA and extracted from CRISIS2014. Black lines correspond to the surficial trace of the fault segmentss, in light blue the projection of fault planes at the surface (taking into account a 15 km depth and the maximum~~.~~ dip angle), in light red the closest fault to FSH (Fessenheim NPP). c) Table containing the principal~~-~~ parameters ~~as exported~~ from BDFA (gray ~~and white~~ columns) ~~table~~ and their transposition into the parametric PSHA fault source model (light green columns). Unknown data are reported Undef or 99 in the BDFA table.

5 Discussion and perspectives

In areas covered by the BDFA, the database represents to date the most complete source of information available in the literature. It is however clear that (1) the database needs to be extended to the entire country (metropolitan as well as neighboring regions) for a wider use than seismic hazards related to nuclear facilities; 2) there is a need for future and periodic updating, especially in some areas such as the Alps and peripheral zones or the Rhine Graben.~~.~~

However, for the time being, we are aware that the data contained in the database are mostly of low resolution as expressed through the robustness index. In metropolitan France, the main reasons for this situation are the following:

- Dating: because surficial deposits were strongly subjected to human reworking and erosion (mostly linked to glaciations), few markers are available to characterize the recent activity of faults (age, slip-rates, etc.~~…~~). In parallel, few Q~~q~~uaternary formations have been the subject of absolute dating campaigns and the ~~question of the~~ age of deformations is often questionable. In this light, projects aiming at developing methodologies (such as the Proyecto Dataciòn performed in Spain, Santanach et al., 2001 ; Shyu et al., 2016 in Taïwan) would help reducing dating uncertainties,
- Pal~~e~~oeseismic evidences and seismic activity: due to the very long ~~return~~ recurrence periods of surface rupturing earthquakes, and because tectonic deformation rates are in the order, or even lower than erosion rates, very few paleoseismic evidences have been identified so far in France. Then, the best way we currently have to estimate the activity of faults is to be able to associate earthquakes, either instrumental or histori~~c~~cal ones. Yet, apart from some temporary local seismic networks (Courboulex et al., 2003, Cushing et al., 2008), we are rarely able to associate the registered seismicity to a specific structure. It is then understandable that such time/cost consuming studies are not sufficiently profitable for researchers in a context of scientific competition. In parallel, new ideas regarding the seismic behavior of stable continental regions (Calais et al., 2016) are sprouting, with the idea that the classical seismic cycle on a fault may not be the most plausible hypothesis and that the seismic potential could be more distributed in space and time. Then, questions related to the definition of what is a stable continental region and how to differentiate faults that ~~would~~ could have the potential to produce major earthquakes from faults that ~~haven't~~ couldn't are of growing importance. In any case, there is a crucial need ~~of~~ for funding data gathering in metropolitan France, but also in regions with comparable geodynamical contexts in order to properly address and ~~argument~~ complement future seismic hazard analysis based on faults;
- Hidden & blind faults: some faults and fault segments without outcropping signatures have been recognized (such as the Belledone fault, Thouvenot et al., 2003) and are integrated into the database. However, studies conducted to highlight them are few in number. In this respect, studies leading to the reprocessing of industrial seismic profiles

are likely to complete our knowledge, as well as studies devoted to relocate instrumental seismicity~~, as well as accurate relocation of instrumental seismicity~~ (Thouvenot et al., 2003~~,~~; Courboulex et al., 2003).

The BDFA project, although it represents the "state of the art" of published studies, is inherently incomplete. It ~~is hoped that it will be~~aims at being useful for identifying and ~~programming~~ planning the scientific campaigns that will be necessary for site specific seismic hazard assessment studies. In this paper we propose~~d~~ a PSHA fault source model based on the transposition of BDFA data in order to conduct an exercise in the Upper Rhine Graben (developed in the parent paper – part B), aiming at quantifying the relative influence of fault parameters on the hazard at a specific site. We underline here that industrial seismic data reprocessed from the GEORG project (http://www.geopotenziale.org/) shows a more complex tectonic pattern in comparison to BDFA, illustrating the need to take into account structures that are not visible at the surface and potentially important to take into account in future hazard analyses. ~~The reason~~ The reason because such dataset was not included~~such dataset could not be included~~ in the BDFA is that additional work, beyond the scope of this study, needs to be done to ~~interpret the structural pattern inferred by~~convert the GEORG structural scheme into BDFA parameters.

We also point out that according to international safety guides (IAEA, 2010), ~~the capable fault issue~~the fault displacement hazard, related to a fault that has a significant potential for displacement at or near the ground surface, should be explored for facilities located in the vicinity of potentially active faults. Th~~e~~is hazard analysis (FDHA) ~~capable fault issue examination~~ however requires a detailed and local dataset as well, that BDFA clearly does not fulfill, but which again represents a guide for future investigations in metropolitan France.

Finally, the ongoing post 2011 Tohoku earthquake discussions have led to envisage extreme events as scenarios against which Nuclear Power Plants need to be prepared. One possible way to foresee these events for SHA purposes may be evaluating the maximum magnitude derived from the sizes of potential earthquake sources (i.e. the active faults). In that sense, the presented database may be useful but additional discussions on criteria to define fault segmentation and consecutively the potential for multi-segment ruptures is needed, as recalled recently by the Kaikoura Earthquake in New-Zealand that ruptured a very high number of fault segments (Hamling et al., 2017)~~.~~.

6 Conclusion

In this paper, we present a first release of a database of potentially active faults ~~database~~ (BDFA) that defines and characterizes faults in their current state of knowledge. ~~This~~ Such a database may be used during the elaboration of fault-based models for future Seismic Hazard Assessment (SHA), either deterministic or probabilistic. In this light, BDFA was designed to include appropriate seismotectonic parameters to do so (geometry, segmentation, slip rate, ~~etc~~etc.).

~~However, BDFA must not be considered as a complete database and therefore cannot substitute for the necessary in-depth studies required to evaluate the hazard at a specific site.~~ This first release of the BDFA results from a ~~work that lasted~~ four years endeavor in defining and compiling the database. Beside problems related to the completeness of some fields and the complete translation in English of the database ~~that needs to be fixed~~(~~project on hold for the time beeing~~in progress), homogenizing the database ~~would~~is ~~be~~ our first ~~effort~~objective for the ~~in the view of a~~ next release. This last point is largely explained by strong regional heterogeneities in data availability. In parallel, a website is currently ~~in~~under construction and will help us gathering more users' feedback~~s~~ to improve the database.

~~However~~As a matter of fact, BDFA must not be considered as a complete database and therefore cannot substitute for the necessary in-depth studies required to evaluate the hazard at a specific site.

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Despite all the care we have taken in the development of this database, it is possible that some errors remain here and there. We then would like to thank in advance all the persons that will contact us in order to share their experience and favor the development and quality of the database.

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