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Seismic hazard in regions of present day low seismic activity: uncertainties in the paleoseismic investigations along the Bree Fault Scarp (Roer Graben, Belgium)

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Abstract

Earthquake hazard assessment in stable continental regions, such as northern Europe, has traditionally been evaluated on the basis of the instrumentally and historically recorded seismicity, which indicates relatively low hazard levels. Reliability of such estimates is a matter of debate as the long-term potential of large earthquakes usually cannot be determined based on short observational periods generally less than a few hundred years. A significant improvement to this lack of knowledge can be achieved by extending the past observations into the geological time scale. Paleoseismic investigations can provide valuable information to bridge this gap, where the potential for large earthquakes can be quantified both in magnitude and recurrence period, based on the observation of prehistoric earthquakes (paleoearthquakes) in the geological record (particularly in the last 20,000 years). However, using these records in seismic hazard analysis requires systematic treatment of uncertainties. Usually uncertainties are inherent to the interpretation of geological record, which leads, in the end, to the identification of paleoearthquakes. Field observations used in the analysis may satisfy several alternative interpretations. Such interpretations become useless when alternative solutions exist but not documented in detail, and especially when the relative reliability of the favored interpretation with respect to the alternative interpretations is not known. The recently introduced method using logic-tree formalism, which is based on qualitative description of the uncertainties related to the paleoseismic data and especially in its interpretation, is applied in the paleoseismic investigations performed on the Bree Fault Scarp, along the Feldbiss Fault (Roer Graben, Belgium). The cumulative uncertainties associated with the different stages of the study are computed as the combination of the preferred alternative branches in the logic-tree presentation. The final uncertainty and its relative importance in seismic hazard analysis is expressed as the paleoseismic quality factor (PQF), which indicate 0.76. This value can directly be used in seismic hazard analysis. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Paleoseismology is a rapidly growing field since its recognition as a distinct discipline in late 1960s and early 1970s (e.g. [11,24,25,28]). Recent developments in paleoseismology (e.g. [13,17,19–21,23,26]) and the importance of the data provided by paleoseismological studies in seismic hazard analysis increase the need for systematic treatment of uncertainties. Uncertainties are inherent in the interpretation of geological phenomena, where field observations may satisfy several alternatives. Quantification of uncertainties related to paleoseismological data in seismic hazard analysis is difficult. Unless documented in detail by the scientist providing such data, using it in seismic hazard analysis may lead to a misinterpretation of the true seismic hazard of an area of interest. The relative reliability of a favored interpretation with respect to the alternatives is rarely quantified. In this paper, a qualitative method of describing uncertainties related to interpretation of paleoseismological data is proposed. The method is illustrated through a simple example using logic-tree formalism applied to the paleoseismological data interpretation process.

2. Stages of interpretation

The main objective of the paleoseismological analysis is important to specify before the treatment of uncertainties. Once this is done, the consecutive stages of analysis can be identified. These different stages may then be integrated into a logic-tree as different nodes with alternative branches. At each node, different alternatives can be described with their associated uncertainties. These uncertainties can be expressed in terms of probabilities assigned to each branch

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Table 1
Tectonic setting and strain-rate with the associated quality weight factors (QWF). QWF values are shown as examples to illustrate the relative ranking

Tectonic setting	Quality weight factor
Plate boundaries (high strain-rate)	0.8–1.0
Active plate interiors (intermediate strain-rate)	0.6–0.8
Stable continental regions (low strain-rate)	0.4–0.6

of the logic-tree. In the simplest case, at each node a minimum of two alternatives can be given, one representing the preferred solution, the other the sum of remaining alternatives. At the end, a joint probability of the preferred alternatives will give a qualitative measure of uncertainty related to the analysis.

In the following, we restrict the discussion to the final stage of paleoseismic investigations where the ’trench-evidence‘ is used to identify the paleoearthquake(s), with a magnitude and date estimate. Paleoseismological interpretation involves the piecing together of complex geological and geomorphic relationships. Important steps in the process may include:

1. tectonic setting and strain-rate;
2. site selection for detailed analysis (site selection criteria);
3. extrapolation of the conclusions drawn from the detailed site analysis to the entire fault;
4. identification of individual paleo-earthquakes (diagnostic criteria);
5. dating of paleo-earthquakes (type of technique);
6. paleo-earthquake size estimates (slip on individual events, correlation between trenches).

3. Tectonic setting and strain-rate

Usually, paleoseismic investigations start with a regional analysis of the recent tectonic deformation, during which a synthesis of different data sets and results is performed. This, together with the already existing relevant data, create the basis of the level of background knowledge. Furthermore, the level of background knowledge is dependent upon the abundance and the visibility of the paleoseismic indicators. The tectonic setting of the area of interest is a controlling factor in the likelihood of producing prominent surface signatures, which can easily be identified in the field. Tectonic setting of the area, being dependent upon the strain-rate, provides the framework in which surface features related to the seismic deformation are developed and preserved and hence is the first factor controlling the degree of reliability of the paleoseismic investigations. In this sense, the three major tectonic environments, i.e. (1) plate boundaries (high strain-rate), (2) active plate interiors (intermediate strain-rate), and (3) stable continental regions (low strain-rate), need to be differentiated and treated separately. Each of these environments (tectonic settings) possess an attached level of uncertainty associated with the paleoseismic indicators used in the investigation. In principle, ranking these three categories relative to each other, would provide a first order approximation of the uncertainties at the initial level of the paleoseismic investigation. A simple example is shown in Table 1. It is important to note here that the three categories defined above are based on the strain-rate and are not equivalent to the three different tectonic environments based on the stress regimes, i.e. (1) extensional, (2) compressional and (3) transverse (strike-slip).

Table 2
Site selection criteria for detailed analysis and the associated quality weight factors (QWF). QWF values are shown as examples to illustrate the relative ranking

Site selection criteria	Quality weight factor
Geomorphic evidence supported by at least two or more geodetic and/or geophysical analyses	0.8–1.0
Geomorphic evidence supported by an additional geodetic or geophysical analysis	0.6–0.8
Geomorphic evidence only	0.4–0.6
Other indirect evidence	< 0.4

4. Site selection for detailed analysis

This is an important stage in the paleoseismic investigations and is often based on geomorphic evidence. Geomorphic evidence is generally critical to the selection of trenching sites, because it includes (1) features that are demonstrably offset and (2) there is a potential for dating the minimum, maximum, average or the ultimate movements. Trench site selection requires understanding of the processes involved in active deformation and is highly dependent on the level of background knowledge about the fault zone at a regional scale to constrain the choice of locality. Abundance of geologic and geomorphic indicators at a local scale and the logistic factors, such as accessibility, permissions for excavation etc., are important considerations influencing the site selection. The reliability of each factor (or indicator) used in the decision process would increase if supported by independent set of observations involving geophysical techniques (e.g. remote sensing, seismic reflection and refraction profiles, ground penetrating radar, gravity and magnetic methods etc.), or geodetic methods (e.g. leveling surveys, GPS-surveys etc.). A simple example is shown in Table 2.

A more objective site selection criteria can be prepared where the different category of indicators can be assigned a quality factor, based on their relative reliability. The use of independent evidence for the observations leading to the trench site selection can for example, be used as having a higher quality factor.

Furthermore, the number and the orientation of the trenches are dependent on the fault type and the inferred sense of slip. In this respect, three basic fault styles: (1) pure dip-slip (normal or reverse); (2) pure strike-slip; and (3) oblique-slip and need to be treated separately. Each category would require a different approach in terms of selecting the sites for detailed investigation. The interpretations made on the above three categories of fault types will have different degrees of reliability related to the degree of difficulty in interpreting these in a two-dimensional trench cross-section. Other practical and logistic limitations, such as the time and financial constrains may also play an important role in the selection of the sites.

5. Extrapolation of site data to the entire fault

Once the detailed site investigations (e.g. trench interpretations) are completed, the conclusions drawn from these are assumed to represent the behavior of the entire fault. This is one of the most important, yet most neglected aspects of the uncertainty related to the paleoseismic investigations.

Usually the trenches represent only a 2–3 m deep section of a fault that may be associated with a complex rupture at depth. Some observations made in a trench may be surface adjustments (response) to a deeper seated tectonic event. Here, in order to assess the amount of extrapolation, a new criteria is proposed, which is expressed by the ratio of the total area excavated through trenches to that of the entire fault area.

TFR is simply the ratio of the total trench area studied to that of the entire fault area. TFR quality factor gives a rough estimate of how much the observational area (trench) is representative of the entire geological structure (i.e. the fault area). This can be simply represented by the following relationship:

$$\mathrm{TFR} = \frac{A_{\mathrm{st}}}{A_{\mathrm{f}}} = \frac{\sum_{i=1}^{n}(T_{\mathrm{l}_i} \times T_{\mathrm{d}_i})}{F_{\mathrm{l}} \times F_{\mathrm{d}}} \tag{1}$$

where A_{st} is the total area of the studied trenches, A_{f} is the total fault area, n is the number of trenches used, T_{l_i} and T_{d_i} are the trench length and depth for the i-th trench, respectively, F_{l} is the fault length and F_{d} is the fault depth. In calculating the TFR, the third dimension of the fault (i.e. width) is neglected assuming planar fault surfaces. However, in certain cases the width (i.e. across-strike width) problem may be more significant than the depth. In some sections of strike-slip faults, the total slip may be concentrated within a few meters of the trace, yet elsewhere (at bends and step-overs) the zone of deformation may be broad. This may even be more problematic for some dip-slip faults, where deformation may have migrated over short periods of time.

A qualitative classification of TFR may then be developed based on five categories, with an associated quality factor (i.e. the assigned weights or probabilities), for the different ranges of TFR. A simple example is shown in Table 3. This classification should take into account the difficulties in opening the trenches especially with respect to the economical feasibility of such studies.

Table 3
A qualitative classification of trench to fault ratio (TFR). QWF values are shown as examples to illustrate the relative ranking

TFR	Qualitative classification	Quality weight factor
0.5–1.0	Very good	0.8–1.0
0.1–0.5	Good	0.6–0.8
0.01–0.1	Moderate	0.4–0.6
0.000001–0.01	Poor	0.2–0.4
< 0.000001	Very poor	< 0.2

6. Identification of paleo-earthquakes

Identification of a paleo-earthquake in a trench is dependent on diagnostic criteria that preclude the possibility of similar structures being created by non-tectonic processes. The reliability of the interpretations done in a trench are therefore reduced when 'non-seismic' features are misinterpreted as the diagnostic criteria. In the following we use the classification of diagnostic paleoseismic features as defined by McCalpin and Nelson [15]. According to their classification there are three different levels (1–3), which correspond to the genesis, location and timing of the paleo-earthquake (Table 4). For the genesis, the diagnostic features can either be primary or secondary. Regarding the location they

Table 4
Three levels of diagnostic features as defined by McCalpin and Nelson [15]

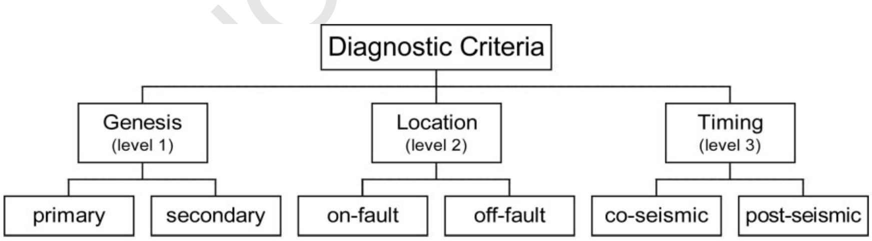

Table 5
Diagnostic criteria (after McCalpin and Nelson [15]). Abundance of similar non-seismic features for each category are indicated in italics

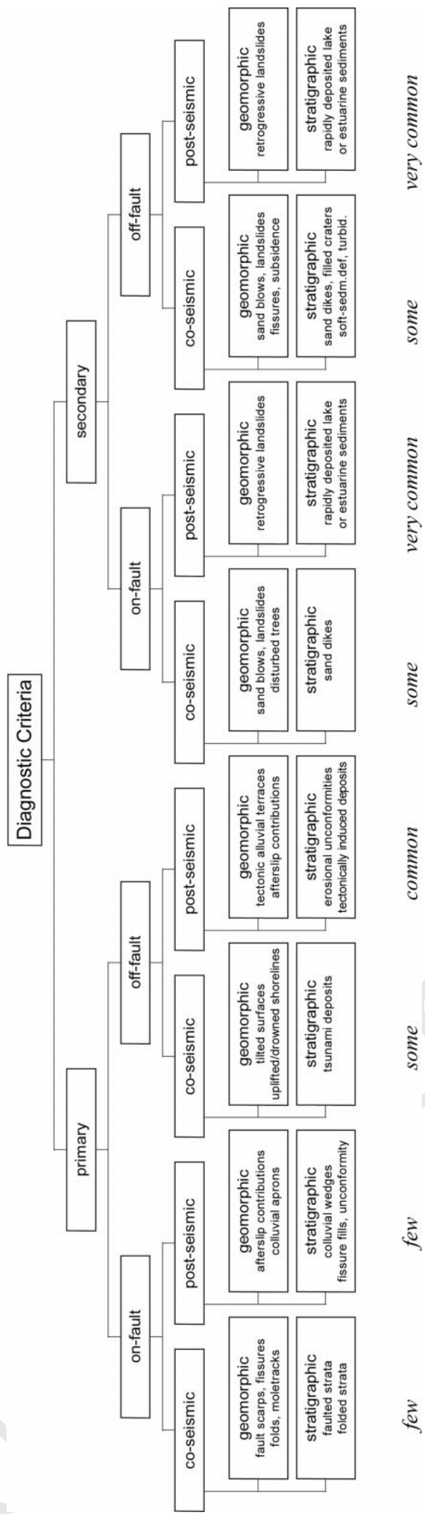

Table 6
Suggested quality weight factors for the reliability of the interpretations related to the diagnostic features (QWF). QWF values are shown as examples to illustrate the relative ranking

Abundance of non-seismic features	Quality weight factor
Few	0.8–1.0
Some	0.6–0.8
Common	0.4–0.6
Very common	<0.4

further divide this into two categories, on-fault and off-fault. Finally, the diagnostic features related to timing are also divided into sub-categories, co-seismic and post-seismic. In addition, each diagnostic feature may be associated with either a geomorphic or stratigraphic expression. As a result, 16 diagnostic criteria are defined, where for each there are other 'non-seismic' phenomena that may produce a similar feature (Table 5). Based on the abundance of these similar non-seismic features, a qualitative measure of the uncertainties for the diagnostic criteria can be prepared. A simple example is shown in Table 6.

7. Dating of paleo-earthquakes

Most dating techniques involve laboratory analyses and numerical processing. In such cases, uncertainties associated with the 'precision' of the measurements are usually quantified. However, high 'precision' in the laboratory analyses and the computational procedures does not necessarily mean high 'accuracy' of the age determination (Table 7). The accuracy of the dating of a paleo-earthquake is dependent on the type of the method used which in turn depends on the type of material available and its stratigraphic position with respect to the horizon in which the paleo-earthquake is identified.

There are a number of different dating techniques used for Holocene deformation, such as; historical records, dendrochronology, ^{14}C, Uranium series, luminescence, lichenometry, progressive landform modification, relative geomorphic position, lithostratigraphy, tephrachronology, fossils, artifacts etc. [15]. These techniques need to be classified according to their relative reliability, where a qualitative weight factor may be assigned to represent the associated uncertainty related to the type of the method. A simple example is shown in Table 8. In addition to the above, any measure of stratigraphic constraints, relations of dated units to faults and resolution of stratigraphic units are important aspects that need to be considered. Here, the knowledge of stratigraphic setting for each of the samples, influences the quality and thus resolution of the resulting estimates of paleo-earthquakes. Furthermore, the numerical uncertainty in the precision of the dating analysis for the chosen method needs to be taken into account to find the total uncertainty associated with the date estimate of the paleo-earthquake.

Table 7
Uncertainties related to the dating of paleo-earthquakes highly depend on the ‘precision’ and the ‘accuracy’ of the results (see text for discussion)

Level of accuracy and precision	Estimates of the date of a paleo-earthquake in time (X marks the correct timing of the event)														
High accuracy–high precision					⊗	⊗	X	⊗	⊗						
High accuracy–low precision			⊗	⊗			X		⊗	⊗					
Low accuracy–high precision							X				⊗	⊗	⊗	⊗	
Low accuracy–low precision	⊗	⊗					X								⊗

8. Paleo-earthquake size estimates

Estimating the size of a paleo-earthquake is based either on primary or secondary evidence. Among the methods using primary evidence, several different criteria are used, such as the surface-rupture length, maximum displacement, average displacement, length times displacement, rupture area and seismic moment. In methods involving secondary evidence, the total area affected by liquefaction and landslides are used as an indirect evidence of the size of the paleo-earthquake. The different methods need to be classified according to their relative reliability and their attached uncertainties should be defined. A simple example is shown in Table 9. Most of these methods are based on the empirical correlation between the historic earthquake magnitudes and the documented behavior of the surface ruptures on historical earthquakes. A number of different regression curves exist for conversion between the surface rupture length and the moment magnitude as well as between the maximum displacement and the moment magnitude (e.g. [30]). The reliability of such regression curves on the other hand, is subject to a number of sources of uncertainty which may result in overestimating or underestimating the paleo-earthquake size [15]. In general, the surface rupture lengths tend to underestimate magnitude systematically, whereas the maximum displacements overestimate. However, the regression based on the surface rupture length seems to have less scatter than that of the maximum displacement [30]. In this respect, rigorous statistical analysis of the empirical data may identify and quantify the sources and amounts of uncertainty.

Here it should be noted that the paleo-earthquake size estimate is highly dependent upon the concept of earthquake segments and fault segmentation. In this respect, fault segmentation vs. events cutting across several segments, overlapping rupture at common segments are important considerations. Definition of the upper-bound magnitude is highly dependent on these concepts. The evidence of events cutting across several segments depend upon the contemporaneity of paleo-earthquakes between study sites on a fault zone or between nearby faults. The contemporaneity can be tested by using the ‘Z-statistic’ (e.g. [12,16,22]). Assuming that the numerical ages determined on a horizon follows a Gaussian distribution, then the overlap of the two ages can be compared given their means and standard deviations in the following way:

$$Z = (A_{eq1} - A_{eq2})/(\sigma_1^2 + \sigma_2^2)^{1/2} \quad (2)$$

where, A_{eq1} is the mean age of the older paleo-earthquake, A_{eq2} is the mean age of the younger paleo-earthquake, σ_1 is the standard deviation of A_{eq1}, and σ_2 is the standard deviation of A_{eq2}. Based on empirically derived curves [16], it is then possible to find the probability of the contemporaneity given the Z-value. When applicable, the Z-value can be used as an additional factor adjusting the uncertainty estimate of the paleo-earthquake and can easily be incorporated into the quality weight factors.

Table 8
Dating techniques and the quality ranking of the associated uncertainties. QWF values are shown as examples to illustrate the relative ranking

Age determination	Method	Quality weight factor
Numerical	Calendar year/Isotopic	0.8–1.0
Calibrated	Radiogenic/Chem. & Biol.	0.6–0.8
Relative	Geomorphic/ Chem. & Biol.	0.4–0.6
Correlated	Geomorphic/Correlation	< 0.4

9. Systematic treatment of uncertainties

A simple method using logic-tree formalism is suggested for systematic treatment of uncertainties in the paleoseismological data. The basic assumption is that each stage of interpretation has an associated level of uncertainty and consecutive stages of interpretation are dependent on the reliability of interpretations made during the previous

Table 9
Earthquake size estimates and the associated uncertainties. Quality weight factors are shown as examples to illustrate the relative ranking

Methods for estimating the paleo-earthquake size	Quality weight factor
I. Methods using primary evidence	
Seismic moment	1.0
> Rupture-area	0.9
> Length × displacement	0.8
> Average displacement	0.8
> Surface-rupture length	0.7
> Maximum displacement	0.6
II. Methods using secondary evidence	
> Liquefaction	0.5
> Landslides	0.4

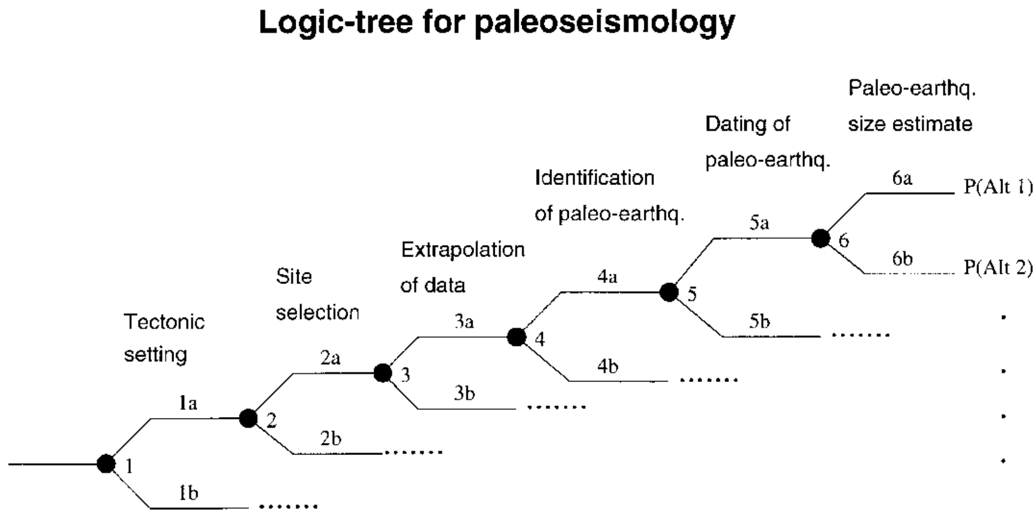

Fig. 1. An example of a logic-tree prepared for the six different stages of paleoseismic interpretation process. At each node, two alternative solutions are shown as two branches, one with the preferred solution and the other representing the remaining alternatives. Total number of end-solutions (Alt1, Alt2, …) in this example is 64. Note that the total probability at each node is equal to unity and the total probability of all the end-solutions is also equal to unity. Probability of the individual end-solutions is calculated as the joint probability for the chosen branches of the logic-tree [i.e. P(Alt 1) = P (1a ∩ 2a ∩ 3a ∩ 4a ∩ 5a ∩ 6a)].

stages. Hence, the cumulative uncertainties provide a guide to the reliability of the end solution.

Two important properties of a logic-tree are important to emphasize here. First, at each branch the total probability is equal to unity and second, the total probability of all the end alternatives is also equal to unity. The total number of alternative end solutions is dependent on the complexity of branching at each node. In the simplest case, there would be at least two alternatives (two new branches) at each node, one representing the preferred alternative and the other representing all possible alternatives (Fig. 1). A simple weighting, in terms of percent probabilities indicating the relative reliability of the chosen (preferred) alternative, can be assigned subjectively at each stage of interpretation (i.e. at each node of the logic-tree). This will give a relative qualitative reliability of the given interpretations with respect to alternative hypothesis. This allows the end-user (in this case the seismologist preparing a seismic hazard analysis) to account for the uncertainties systematically.

In the case where the scientist is completely in control of all other alternative solutions at each node of the logic-tree, the full logic-tree can be provided in a complete form. This will allow the end-user to apply a more complete analysis by being able to use the distribution of probabilities in the alternative end solutions. This is a common procedure in probabilistic seismic-hazard analyses and any desired level of uncertainty can be chosen (e.g. median, 15th percentile, 85th percentile, etc.), ranging from the least conservative to most conservative solution.

10. Application to seismic hazard-analysis

The logic-tree analysis proposed above provides an overall estimate of the uncertainties associated with the preferred interpretation in a paleoseismological investigation. The possible application to seismic-hazard analysis requires an additional step interfacing the logic-tree for the paleoseismological uncertainty analysis with the logic-tree that will be used to account for the uncertainties in the seismic hazard-analysis as a whole. This interface is explained in the following.

The resulting value of an end-solution (probability) for the combination of the preferred alternatives (i.e. the path followed in the logic-tree) may be used as a factor reflecting the 'quality' of the paleoseismic investigation. Here, we introduce a new term 'paleoseismic quality factor (PQF)' which is expressed by the following:

$$\mathrm{PQF} = P_{\mathrm{es}} \times C_{\mathrm{ri}} \quad (3)$$

where, P_{es} is the probability of the preferred end-solution in the logic-tree analysis for the paleoseismic investigation and C_{ri} is a correction term for the relative level of importance of the investigation in the seismic hazard analysis. These relative levels of importance may be grouped into five categories:

- Level 1: type of paleoseismic investigations, which provide estimates for upper-bound earthquake magnitude and recurrence on a specific fault. Includes site-specific seismic-hazard analyses (probabilistic or deterministic) where the results from the paleoseismological investigation have a direct impact.
- Level 2: type of paleoseismic studies where the results are used as the earthquake recurrence and the upper-bound magnitude estimates for the line sources in a regional seismic-hazard analysis.
- Level 3: type of paleoseismic studies where the results

are used as a single-entry (paleo-earthquake) to an earthquake catalogue, which later are used in the computation of the input parameters for the area and/or line sources.
- Level 4: the aim of paleoseismic investigation is to assess the earthquake potential of a fault zone and will not be used directly in the seismic hazard analysis.
- Level 5: the aim of the paleoseismic investigation is only to prove that the fault zone is active (i.e. co-seismic surface deformation during the Holocene and late Pleistocene).

The aim of the paleoseismic investigation is critical to define the level of importance. If the objective of the investigation is only to prove that the fault or fault zone is active (e.g. Level 5), the degree of importance is completely different than using the results directly in a site-specific seismic-hazard analysis of a nuclear power plant (e.g. Level 1). The five different levels suggested here should therefore be taken into account in the total uncertainty of the system. A simple example is shown in Table 10. A level of uncertainty, which is acceptable in one category may be intolerable in another.

Table 10
The level of importance of the paleoseismological results which have implications in the following seismic hazard analysis and the corresponding correction terms C_{ri}. Values suggested for the correction term (C_{ri}), are shown as examples to illustrate the relative ranking between the different level of importance categories

Level of importance	Correction term C_{ri}
Level 1	2
Level 2	4
Level 3	6
Level 4	8
Level 5	10

11. A case study in northern Europe

In order to illustrate the proposed methodology, a recent paleoseismic investigation along the Bree Fault Scarp (Roer Graben, Belgium) is used as an example. The individual steps as described earlier in the text are applied to this case study. In the following, the uncertainties associated with the evidence used in the different stages of the investigation are described. For more details on the different aspects of the investigation, the reader is referred to the recent publications concerning active tectonics in this area (e.g. [3,4]).

Large and damaging earthquakes in the low seismicity intraplate regions, such as north-western Europe, are virtually unknown. Seismic catalogues, covering the last six centuries, list a number of moderate size events for this region (Fig. 2). However, the occurrence of the 13 April 1992 Roermond earthquake (Ms = 5.3) prompted questions on the potential of similar or even larger earthquakes in the Rhine graben system [5]. In response, the Bree Fault Scarp along the Feldbiss Fault (Roer Graben, Belgium) is studied in detail to characterise late Pleistocene and Holocene tectonic deformations and the related paleoearthquakes [3,4]. Different methodologies were used for the paleoseismic investigation including a detailed geomorphic analysis, geophysical methods and later trenching along the fault scarp [3]. The analysis revealed evidence of past seismic events, having produced coseismic surface ruptures and suggest that three earthquakes probably occurred during the last 14,000 years, the latest one taking place between 610 AD and 890 AD. The vertical offset of 0.6 m, combined with a minimum fault length of 10 km, implies a $M_W \geq 6.3$. Furthermore, from the paleoseismic investigation an earthquake return period ranging from 4000 to 8000 years and a vertical deformation rate of 0.10 ± 0.06 mm year^{-1} are inferred.

In the following sections, the proposed method is used applying the individual steps outlined earlier in the text.

11.1. Tectonic setting/strain-rate

The area discussed in this case study is situated in an active plate interior, where the strain-rate is classified under intermediate strain-rate (0.01–0.1 mm/year). Suggested quality weight factor (QWF) based on the classification used in Table 1, is in the range (0.6–0.8). Here, a QWF of 0.8 is assigned, taking into account the visibility of the fault scarp morphology along approximately 10 km length of the fault.

11.2. Site selection

Selection criteria used in the location of the four trenches excavated along the Bree Fault Scarp, were based on extensive geophysical and geomorphologic analysis. Since almost all earthquake focal mechanisms indicate normal faulting in this area, all four trenches were opened perpendicular to the fault scarp. Following is a summary of the site selection criteria used in this study.

Low resolution seismic reflection surveys conducted by the Belgian Geological Survey [9,10] located the major fault branches in the Roer Graben fairly accurately. These were confirmed by intermediate resolution surveys on the Campine canals [7,8]. A combination of results from reflection studies and those inferred from earthquake data showed normal faulting extending from the ground surface to a depth of about 17–20 km in the seismogenic layer [14] (Fig. 3). Geomorphological studies were then performed in the area that clearly showed the Bree Fault Scarp [1]. Through levelling profiles along the scarp, it was possible to identify a significant vertical displacement. Fig. 4 shows clearly a NW–SE oriented escarpment, south-east of the town of Bree. This is an expression of the Feldbiss Fault which is a boundary fault between the elevated Campine plateau and the Roer Valley graben [1,3,18].

Along the Bree Fault Scarp a number of high resolution geophysical surveys were conducted [14], including the

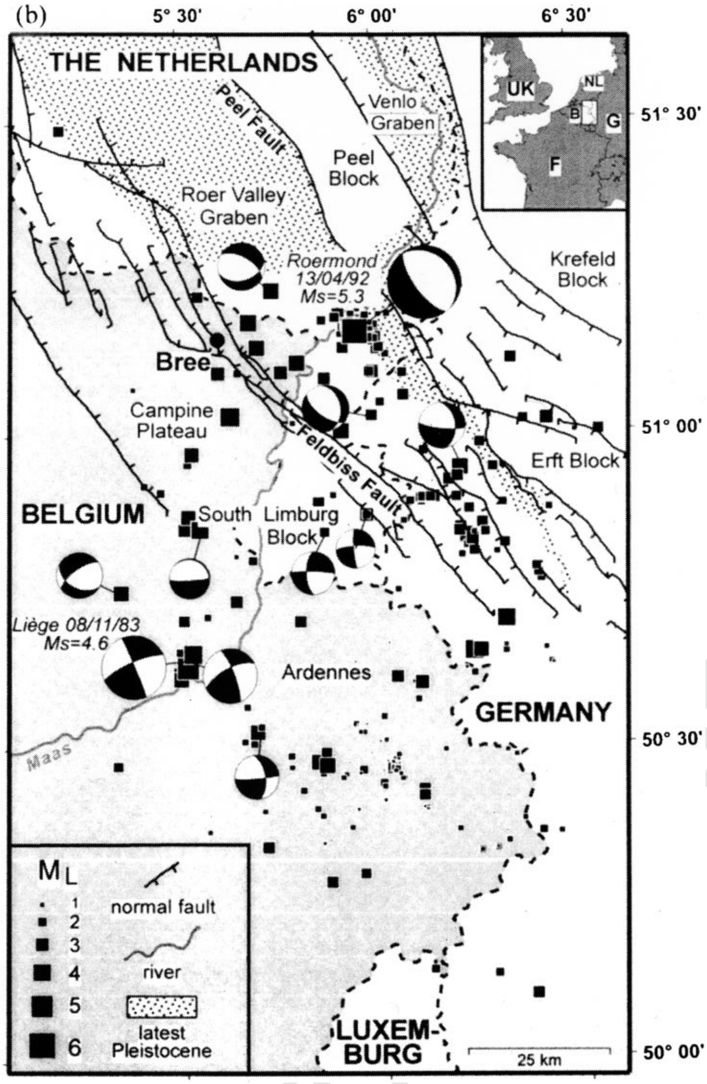

Fig. 2. Seismotectonic map of the Roer Graben and surrounding areas (from [4]). Focal mechanisms are compiled from the work of Camelbeeck and van Eck [5].

following methods: (1) refraction seismic survey; (2) electrical profiling and tomography; (3) electromagnetic profiling; and (4) ground penetrating radar. Site selection for the trenches were primarily based on the results from these methods. Fig. 5 shows the summary of the results obtained from the site where the first trench was later opened.

The position of recent sediments in the river valley on the down-thrown block, as well as, logistics, accessibility, and local permissions, played a role in the final selection of the four trench sites. Using the classification suggested in Table 2, the assigned QWF is 0.9.

11.3. Extrapolation of data

In the analysis, different observations collected along the fault scarp (i.e. in the four excavated trenches) were assumed to be representative of the behavior of the entire fault. In order to determine the reliability of this assumption, the trench to fault ratio (TFR), is calculated. Using the approximate fault dimensions based on the 10 km length of the scarp and the 17 km depth of the seismogenic zone, and trench dimensions for each trench of 100 m (length) × 4 m (depth), the TFR is given as:

$$\mathrm{TFR} = \frac{100 \times 4 \times 4}{10000 \times 17000} = 0.0000094$$

The ratio falls under the poor qualitative classification based on the QWF values suggested in Table 3 (i.e. the QWF range of 0.2–0.4). However, the geomorphic expression of the fault scarp, being observed as a consistent linear feature approximately 10 km, is used as an argument to assign a higher QWF value. Furthermore, the four trenches were separated uniformly along the entire fault and the observations from the trenches were coherent [4,6]. A quality weight factor of 0.75 is therefore assigned.

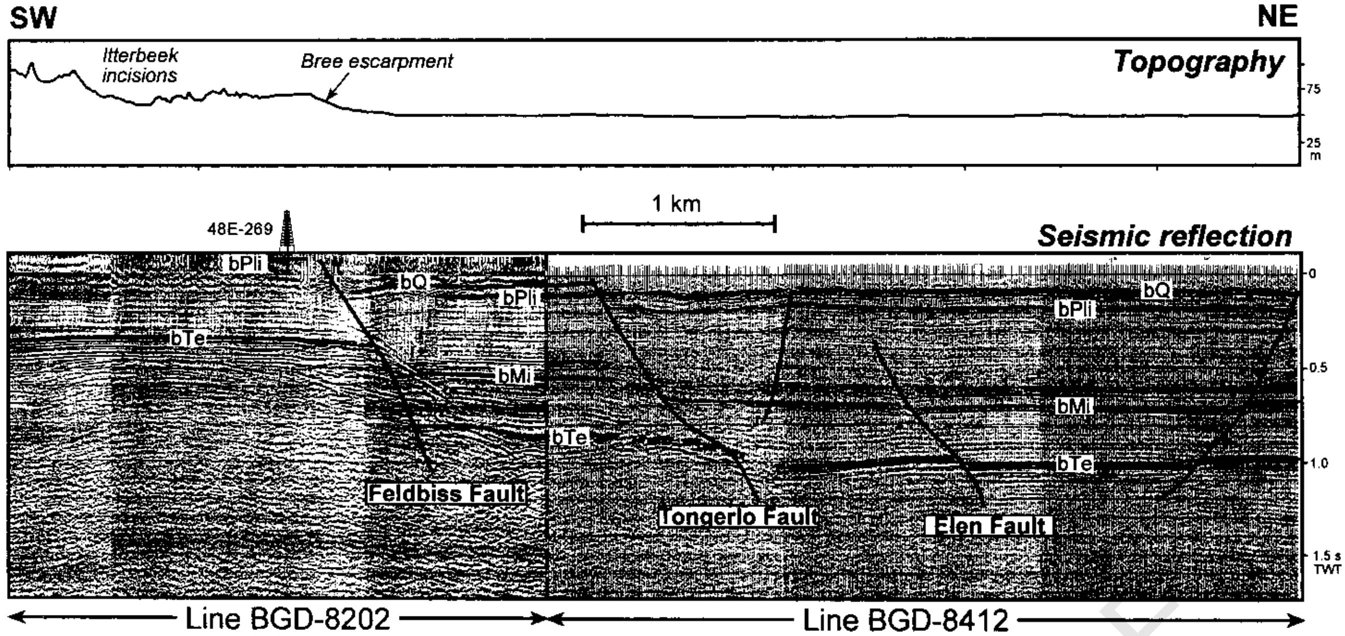

Fig. 3. Seismic profile and the corresponding topography produced by the Belgian Geological Survey across the Feldbiss Fault (from [4]). Stratigraphy slightly modifed from Demyttenaere and Laga [10]: bQ = base Quaternary; bPli = base Pliocene; bMi = base Miocene; bTc = base Tertiary.

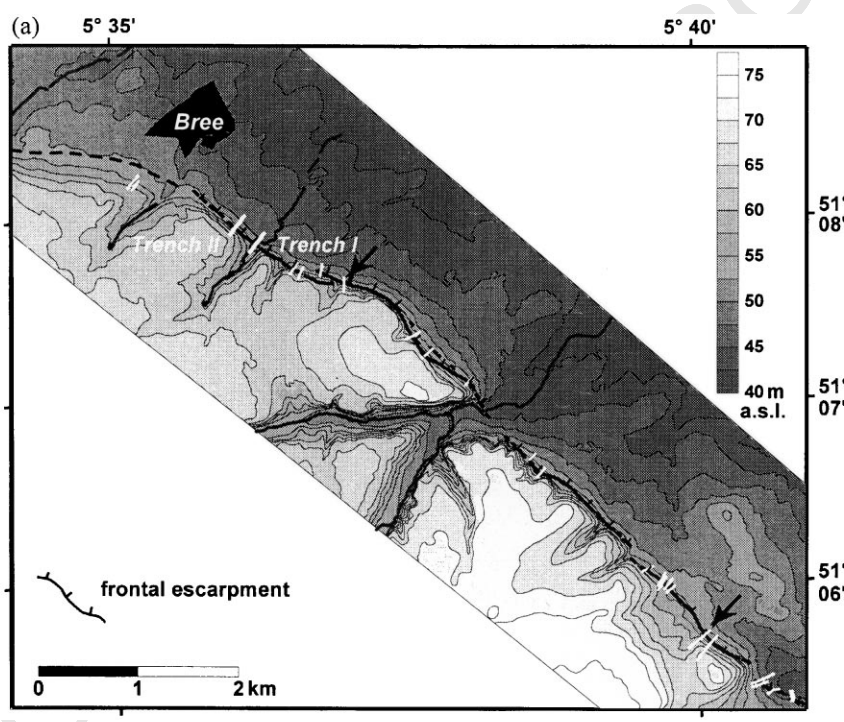

Fig. 4. Morphotectonic map showing the main section of the Bree Fault Scarp (from [4]). The site of trench investigations and levelling profiles are shown in white across the scarp.

11.4. Identification of paleo-earthquakes

Based on the interpretations made on the trench logs three paleo-earthquakes were identified. As described in the previous sections, uncertainties are defined according to the reliability of the diagnostic criteria used in identifying the paleoearthquakes. According to the classification suggested by McCalpin and Nelson [15], the diagnostic features observed in the trenches were of primary origin, on the fault and co-seismic. In all four trenches, the

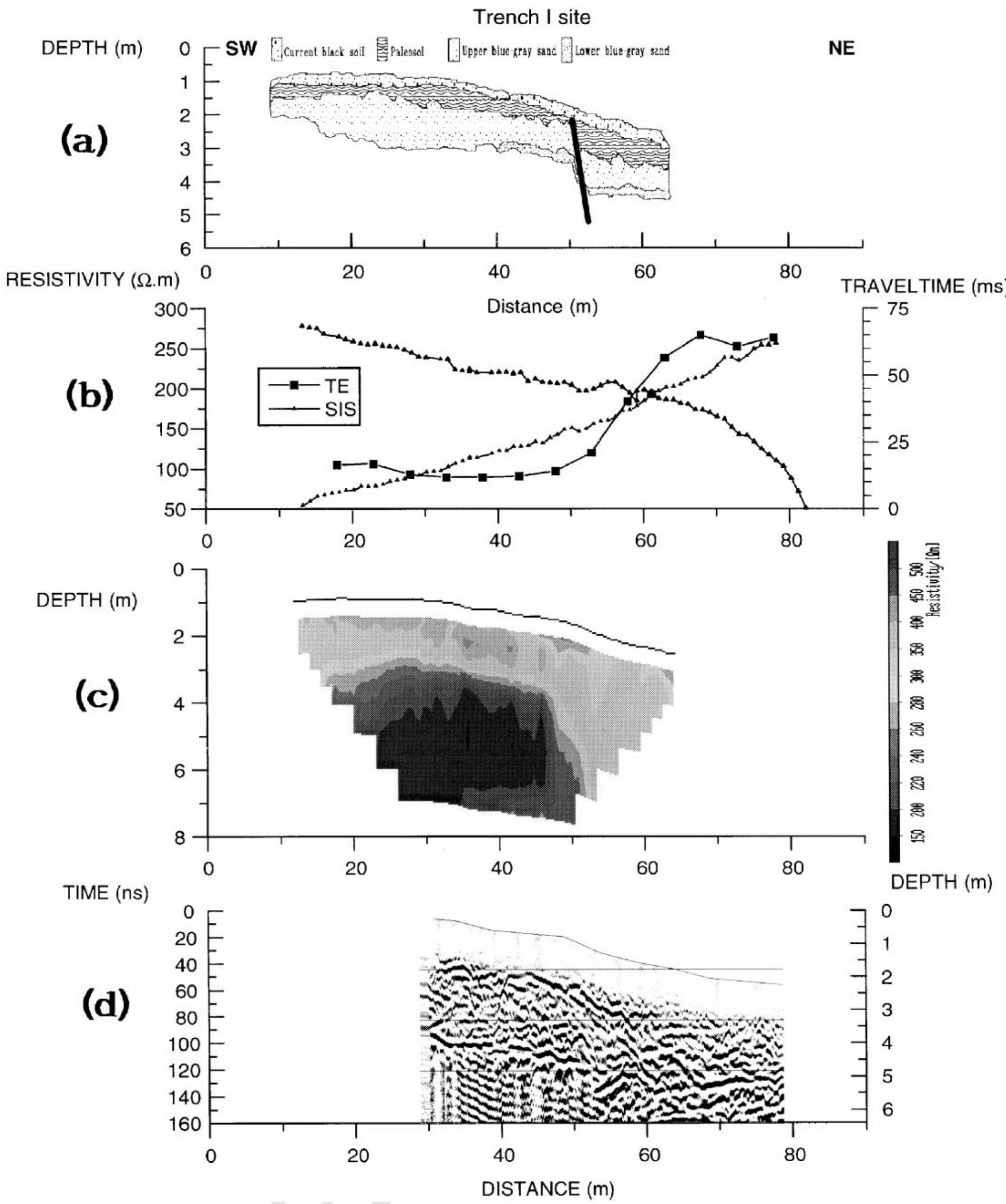

Fig. 5. Summary of the high resolution geophysical profiles obtained at the first trench site (courtesy of Denis Jongmans, University of Liege). (a) Sediment log for Trench I; (b) geo-electrical resistivity and seismic refraction; (c) electrical tomography; (d) ground penetrating radar.

evidence used for identifying the paleoearthquakes were based on disrupted stratigraphic horizons and colluvial wedges indicating vertical offset (Fig. 6). There was additional evidence from secondary criteria, both on and off the fault. These included soft sediment deformation and liquefaction, believed to have been caused by seismic shaking [27]. Secondary off-fault evidence included a swampy zone formed after the Maas river tributary channel deviated from its original bed. This was due to the tilting of the uplifted block during several earthquakes [4]. However, some of the secondary features could also be explained by non-seismic phenomena. It could be argued for example, that these were formed by periglacial features and that the observed scarp could have been enhanced by fluvial erosion. Countering evidence to support vertical co-seismic displacement, on the other hand, includes hand-cores that showed layering consistent with fault displacement. This was further supported by the results from the ground penetrating radar performed along the trench floor, which indicated an abrupt change in the character of the reflectors on both sides of the fault (i.e. flat-lying reflectors on the down-thrown block) and the fault line was observed clearly to a depth of several meters below the trench floor. Additionally, 20 m of difference in the elevation along the slope between the Campine block and the Bocholt plain could only have been generated by the fault. The argument is further supported by the

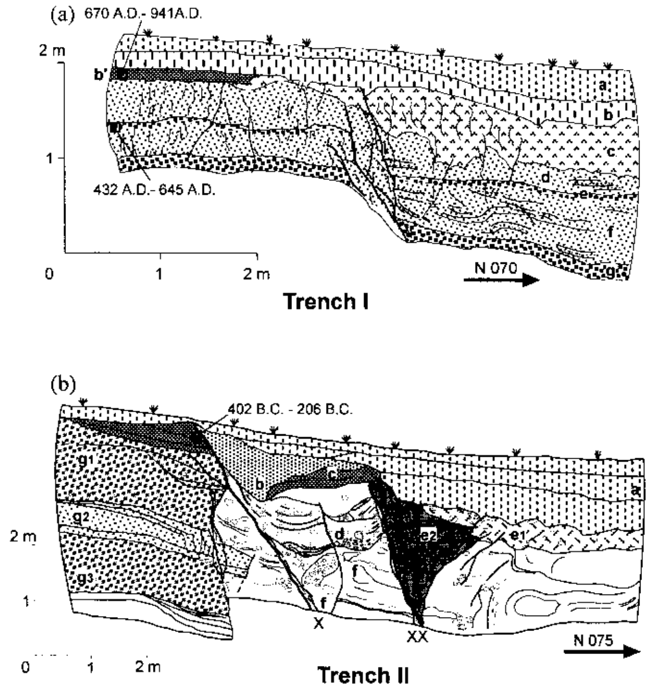

Fig. 6. (a) Central section of Trench I. Holocene alluvial deposits are affected by the normal fault and 0.5 m of vertical offset can be measured from the displaced units g and e (coarse and fine gravel horizons, respectively). Units f and d are sandy deposits with channel incisions and minor faults. Paleosoil c, which wedges out against the fault, has registered the latest faulting event; (b) Upper section of Trench II, displaying two clear fault branches X and XX. The last three faulting events can be retrieved from the colluvial wedges e, d and b (both cross-sections are from [4]).

observations that the stratigraphy of the Campine plateau and the Bocholt plain are completely different.

Taking into account the above line of arguments, only a few non-seismic phenomena could have produced the same diagnostic features used in the identification of the paleo-earthquakes. Based on the classification criteria shown on Tables 4–6, the quality weight factor of 0.75 is assigned.

11.5. Dating of paleo-earthquakes

In the case study ^{14}C dating was used to determine the date of the organic material from the sedimentary deposits in the trenches [4]. Dating results indicated that in total, three paleo-earthquakes were identified to have occurred in the last 40 Ka, with two in the last 30 Ka. Assuming a uniform time distribution of earthquakes, an average return period of 12 ± 5 Ka was inferred. According to the quality weight factors suggested in Table 8, numerical methods would give a QWF within the range 0.8–1.0. However, taking into account the difference between ‘precision’ and ‘accuracy’ (Table 7) of the obtained results, a lower quality weight factor of 0.5 is assigned.

11.6. Paleo-earthquake size estimates

The seismic moment for the last identified surface faulting earthquake was calculated by assuming the whole seismogenic layer (about 17 km thick) ruptured over a minimum length corresponding to the length of the Bree Fault Scarp (10 km) along the Feldbiss Fault. The average vertical offset of 0.6 m, combined with a minimum fault length of 10 km, implies a $M_W \geq 6.3$ [4]. Using the suggested QWF values shown in Table 9, a quality weight factor of 0.75 was assigned.

11.7. Treatment of uncertainties

Applying the logic-tree formalism in the proposed method, the probability of the preferred end solution in the analysis is found to be $P_{es} = 0.15$ (Fig. 7). Assuming that the obtained results in the above example will be used as the earthquake recurrence and upper-bound magni-

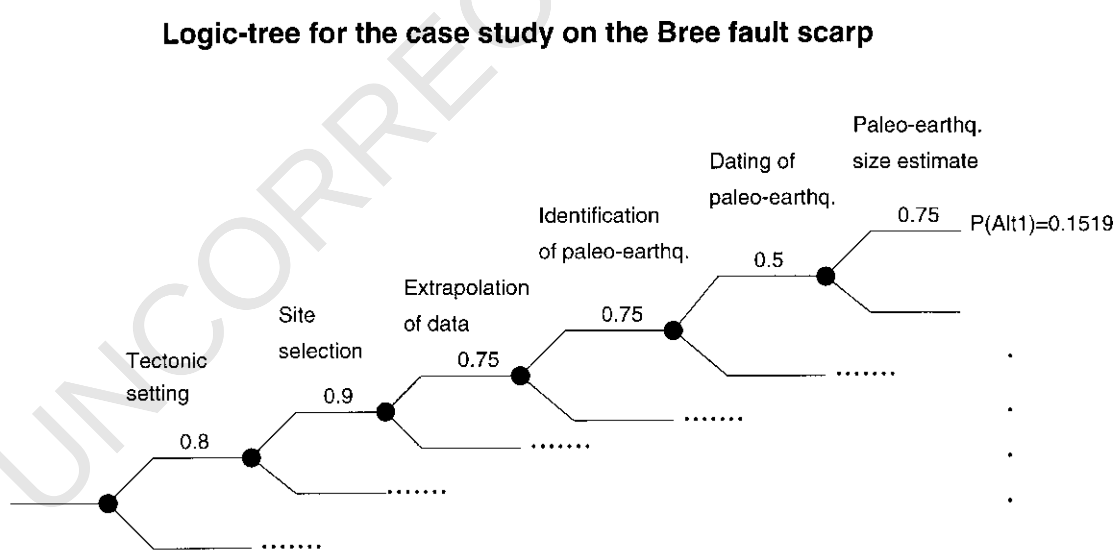

Fig. 7. Logic-tree showing the uncertainties associated with the six different stages of the paleoseismic investigation conducted on the Bree Fault Scarp (Roer Graben, Belgium). In this case, P(Alt1) indicates the preferred end solution P_{es}, which is calculated as 0.15.

tudes for the line sources in a regional probabilistic seismic-hazard analysis for the area, importance Level 2 may be applied (Table 10). In such a case, the PQF will be 0.60.

In the above, the case study for the Bree Fault Scarp is shown as an example for illustrating the application of the method. However, it should be noted that the calculated PQF value (assuming Level 2) reflects the uncertainties associated with the present stage of the investigation. The study is still in progress and additional analyses will be required to improve the PQF value. Furthermore, it is not possible to compare the significance of the PQF value obtained for this study relative to other paleoseismic investigations. The method will be better utilized when it is applied to a sufficient number of case studies where the relative significance of the PQF values are established.

12. Discussion

In the proposed method, some of the fundamental uncertainties are not included as a part of the six defined stages of interpretations. These are basically related to the completeness of the paleoseismic record. Many trenches may contain an incomplete stratigraphic record of paleo-earthquakes and therefore bias the interpretations. Here, a major factor influencing the completeness is the problem of preservation of evidence. This is dependent upon the relative rates of erosion and deposition versus the rate of deformation (e.g. [2,29]). Depending upon the climatic conditions and lithology, the paleoseismic evidence may be partly or completely eroded away. Significant co-seismic displacements are needed to preserve the evidence that can reliably be used later in the interpretations. The problem related to the preservation of evidence affects a number of stages in the paleoseismic investigation, such as the trench site selection, diagnostic criteria used in the identification of paleo-earthquakes and the paleo-earthquake size estimate. It is therefore important that the uncertainties associated with the incompleteness of the paleoseismic record and the preservation of evidence should be included at the initial stage of the uncertainty analysis. Since the regional understanding of the area of interest is closely related to the tectonic setting and the strain-rate, the assigned uncertainties for the first stage may then be considered to account also for these.

Appreciation of the time perspective of the processes involved is another important aspect in the analysis of the uncertainties. Here, two important issues require special attention. First, the difficulties in matching the long-term deformation rates with the known co-seismic slip (i.e. problem of identifying the existence and the amount of creep associated with the observed displacements) and second, whether the maximum observed slip at a given fault is a result of a single or several paleo-earthquakes. Uncertainties associated with these, need to be taken into consideration during the relevant stages of interpretation.

In this paper, a simple method is proposed for systematic treatment of uncertainties in paleoseismic investigations. The intention of the proposed methodology is to improve the existing problems in the documentation of the uncertainties. Here, it should be emphasized that the quality weight factors suggested in Tables 1–10 are only meant as simple examples to illustrate the relative ranking of the different categories and therefore may not represent appropriate values. Appropriate quality weight factors for different categories at each stage should be prepared by a careful and systematic examination of a large number of paleoseismic investigations. This can only be achieved by a group of experts working actively in this field using empirical data from a large number of uncertainty analyses and is therefore beyond the scope of the present work.

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