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Probabilistic seismic hazard assessment in France;. Part One : seismotectonic zonation

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ABSTRACT: In order to develop the probabilistic approach to seismic hazard for conventional buildings in France, the AFPS has created a working group (EPAS : Evaluation Probabiliste de l'Aléa Sismique - Probabilistic Seismic Hazard Assessment) with the objective of harmonizing methods and obtaining firstly a consensual zonation, necessary as a support for identifying the seismicity distribution law, and secondly making a probabilistic hazard map that can be used as a basis for regulation. The second step is detailed in the next abstract (part two) and uses the seismotectonic zonation to compute the probabilistic map. Since different groups of experts may adopt different methods of determining a seismostectonic zonation, a major effort was made to define parameters to be considered and on harmonization of the methodological approach. The result of this work is the development of a methodology that can be used for defining seismotectonic zonation all over France for the first time. Sections on the scale of the earth's crust support the justifications for the boundaries of this zonation.

1 OBJECTIVE AND GENERAL PROCEDURE

The probabilistic evaluation of the seismic hazard is very little used in practice in France. Standard practice for the evaluation of seismic hazard for "special risk" (nuclear plants, chemical plants, dams, ...) structures uses a deterministic approach based essentially on determination of seismotectonic domains (surface source areas) and/or seismic faults. For "normal risk" structures, the seismic level is determined using a statistical method based on historical seismicity (Despeyroux and Godefroy, 1986). The AFPS would like to take into account recent developments in the practical determination of seismic hazard and has decided to create a working group in order to develop a probabilistic approach applied to conventional buildings, particularly in order to harmonize methods used for structures with "special risks" and with "normal risks" (public buildings and equipments). It was decided that the representative period would be 475 years, which is frequently assumed in evaluating the seismic hazard for conventional buildings. For a period of this order of magnitude, it is considered that knowledge obtained over 500 to 1000 years of historical seismicity is sufficient. This zonation must consider all zones determined as being equipotentionally seismogenic. The level of detail in accident families and individual faults was not considered, mainly due to spatial distribution of the historical seismicity; the seismicity sample is smaller for a smaller area. In general, the procedure uses all parameters that are significant for seismogenesis; the structure of the crust and its sedimentary cover, the way recent and current stresses and deformations are distributed, the distribution and typology of instrumental and historic seismicity.

The working group consists of experts currently involved in defining zones necessary to determine the seismic hazard for risk industries in France (Nuclear and Classified Installations). About ten meetings were necessary to harmonize approaches and to determine a seismotectonic zonation.

This was then submitted to the scientific community for criticism and validation.

The main criticisms concerned:

-justification of the procedure and themes chosen to characterize the current state of deformation of the brittle continental crust,

-the choice of some zone boundaries and their expression at depth.

2 SEISMOTECTONIC ZONATION FOR A PROBABILISTIC APPROACH

A consensual methodological approach was adopted by all experts. The various zones existing across France presented by the various organizations (IPSN/GEO-TER, BRGM, EDF) were built at different periods with the objectives of a deterministic application of the seismic hazard.

– seismotectonic zonation in France, in " Sismotectonique de la France métropolitaine dans son cadre géologique et géophysique " (Grellet et al., 1993).

– Map of seismotectonic units in " Zonage sismique de la France pour l'application des règles parasismiques aux installations classées " (Blès et al., 1996).

– Different regional seismotectonic zonations used for nuclear and classified installations in France.

In these various zonations preference is often given to some geological, geophysical, geodynamic or neotectonic data, sometimes to the detriment of the representativeness of historical and instrumental seismic activity. Consequently, a completely new methodological study has been undertaken in order to set up a common zonation strategy.

In a subject with intracontinental deformation like France, the structural parameters that appear to depend on seismogenesis are related to the nature and the current structure of the brittle continental crust (average thickness across France 15 to 25 km).

To characterize these parameters, the choice of study themes was guided by:

– the nature of the brittle crust and the history of deformation applied to this crust since about 300 million years,

– the fact that the more recent geodynamic phenomena (alpine tectonics over the last 25 million years) are more closely related to current seismogenesis,

– the assumption that the 1000 years of knowledge of the distribution of seismicity in France is statistically representative of the main crustal discontinuities.

2.1 *Defining zonation*

The procedure consists in making intermediate zonation for each of the selected themes, and then comparing them (Fig. 1).

– A first "main structural inheritance" zonation was thus made (fig. 1). This zonation takes into account the state of the crust by adding the effects of the various tectonic structures (major boundaries of the hercynian chain and the cadomian block, crustal thickening induced by alpine orogenesis (in the broad sense of the term) and crustal thinning induced by rifting phases (oligocene, then neogene and quaternary). The geophysical themes (gravimetry, magnetism, representation of the Moho depth with isobaths) complete this approach.

One major difficulty encountered in preparing this zonation is due to the presence of sedimentary basins where clear boundaries or even transition limits remain uncertain. Their aseismic or slightly seismic aspect was taken into account in the zonation of their seismic activity.

– The second zonation, reveals the influence of the distribution of recent and current deformation types (Fig. 2). This theme is largely represented by the seismotectonic zonation given by the IPSN document (Grellet et al, 1993). The combination of these two zonations resulted in a single zonation (fig. 3) that includes the crust structure and its dynamic behavior except for the distribution of earthquakes that will be included in the next zonation. This is obtained by superposing overlays from previous zonations, locally compared to stress field data (focal mechanisms, in situ stress measurements).

– A partial zonation of the seismicity distribution (fig. 4) was prepared, considering only the boundaries that are very specific (concentrations, multiple, clusters), or that provide decisive information about other previously defined zones.

The summary represents the seismotectonic zonation to be taken into account for a probabilistic method. This zonation was submitted to a scientific reading committee and was modified to take account their comments (fig. 5). Main corrections take into account geophysical informations (Autran et al., 1994) and local modifications. The resulting map is presented figure 5.

2.2 - *Zonation boundaries*

Hierachization of boundaries is an essential component of a probabilistic approach, since it may be necessary to group some areas to increase the seismic sample to be considered in a calculation. Hierarchization gives a weight to these boundaries, which may lead to grouping of zones with similar seismotectonic parameters.

Level 1 boundaries (major or principal) correspond to the influence front of the most recent major geodynamic processes, namely:

- the West-European rifting, crustal thinning and the Gulf of Lion opening,
- the development of the Alpine chain (Alps and Pyrénées) associated with crustal thickening.

The major crustal scale contrast corresponds to the outermost envelope of the alpine deformation that makes a transition with the European platform.
All of these data correspond to a crust with high deformation gradients involving the continental crust and sometimes even the lithosphere.

Level 2 boundaries (secondary) correspond to marked transitions between domains with strong mobilization of the hercynian structural inheritance during the alpine episode (SL) and slightly deformed or undeformed sedimentary basins.

Level 3 boundaries (uncertain or imprecise) concern all weakly expressed transitions which are not fundamentally explained by structural elements (for example seismicity boundaries, gradual transition of structural parameters).
A qualitative degree of confidence is applied to each of these boundaries:

- solid line = clearly defined boundaries (fault, fault systems),
- dotted line = gradual transition, poorly defined boundaries, boundaries of geophysical characteristics.

Model boundaries are imposed around the periphery of the territory in order to be able to close the zones (requiried by the model).

"Test" boundaries correspond to concentrated areas of badly explained earthquakes (e.g. Bordeaux cluster) in order to test their influence on the probabilistic method for seismic hazard.
If possible, each of the boundaries is defined and characterized using deep geological and geophysical sections, the seismicity and the main available geophysical profiles (ECORS, etc.) in order to display their geometry in three dimensions (fig 6 and 7).

The characterization of each boundary is explained in table 1.

3 CONCLUSIONS

For the first time in France, seismotectonic zonation is proposed for probabilistic assessment of the seismic hazard across the entire country (figure 5). This zonation is based on seismotectonic criteria considerations originating from an analysis of geological, geophysical and seismological data.

The methodology used is based on experience gained by a large number of professionals (geologists and seismologists) and scientists representing the various public and private organizations carrying out seismic hazard studies in France (Nuclear installations, Classified Installations, dams, conventional buildings). This new tool is available to anyone who would like to test a probabilistic assessment of the seismic hazard within France.

In order to improve the preparation of a model describing the characteristics of the seismic activity in source zones, it was decided to improve the seismotectonic zonation map by searching for possible links between deep geological structures and the depth parameter of earthquakes, obtained from historical data and from instrumental data.

For this new step to be carried out, it is necessary to take stock of the results and to analyze all the recent results of national and international (boundary countries) research programs (GPF - Deep Geology of France) program, ECORS, major oil exploration seismic profiles, ...) in order to obtain a three-dimensional image of the earth's crust. Zonation is only a surface mapping representation and earthquakes usually occur at the transition between the ductile/brittle crust at a depth of about 10 to 15 km.

Thus, a map of seismic areas is offered, but particularly and especially this seismic activity can be displayed with the deep structures to which it is related and that caused these earthquakes.

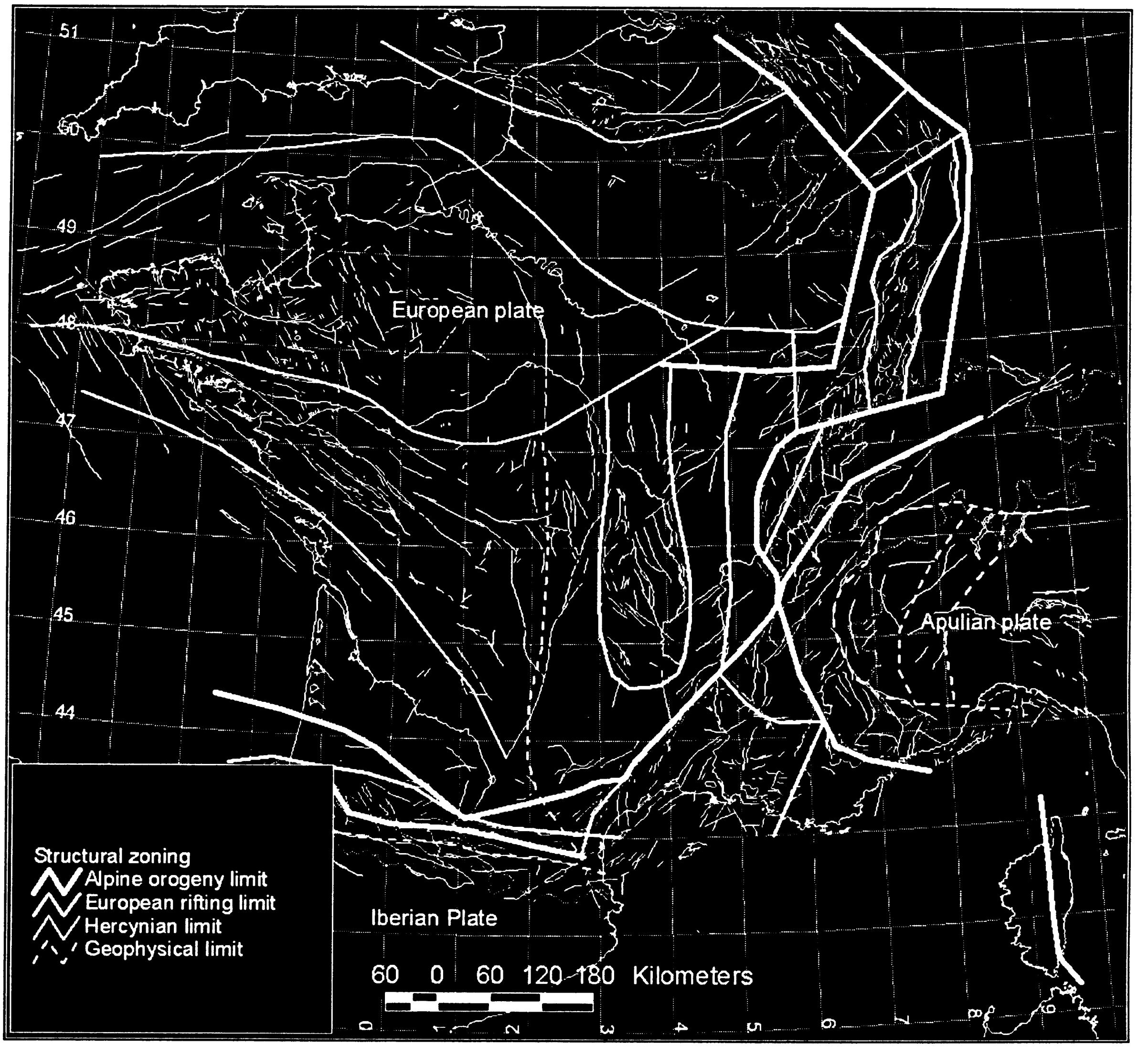

Figure 1 : Structural zonation.

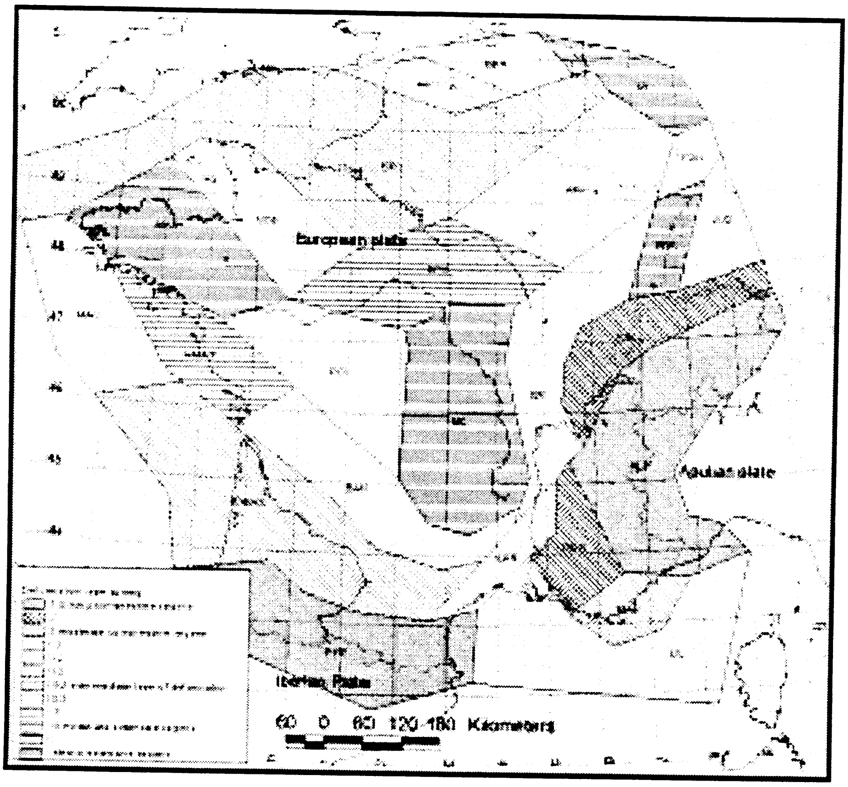

Figure 2 : Current deformation types zonation

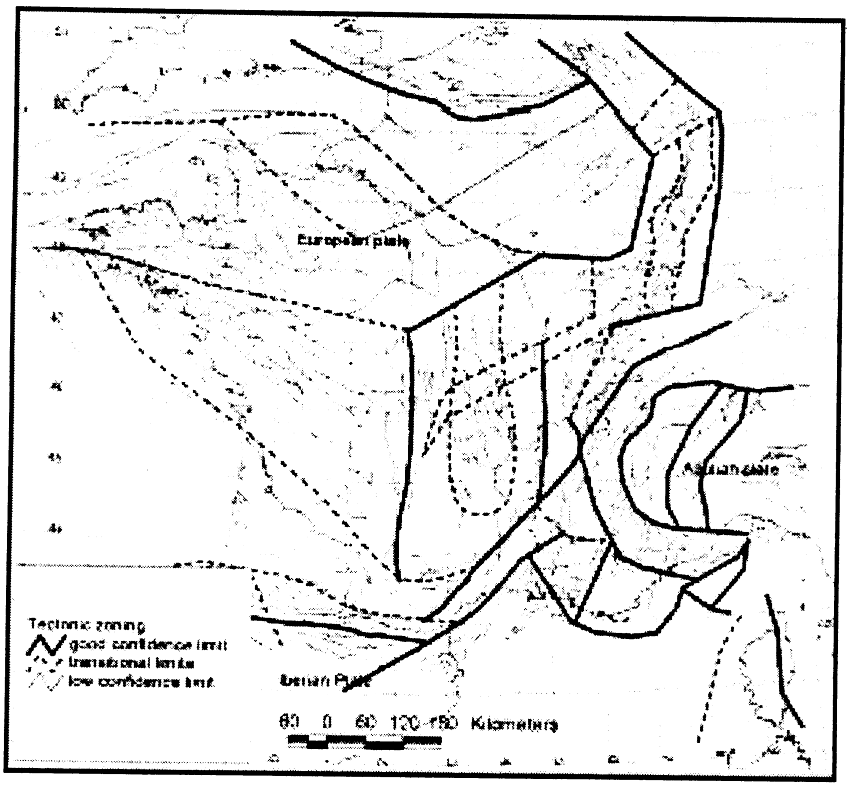

Figure 3: Combination of the figure 1. and figure 2. zonations

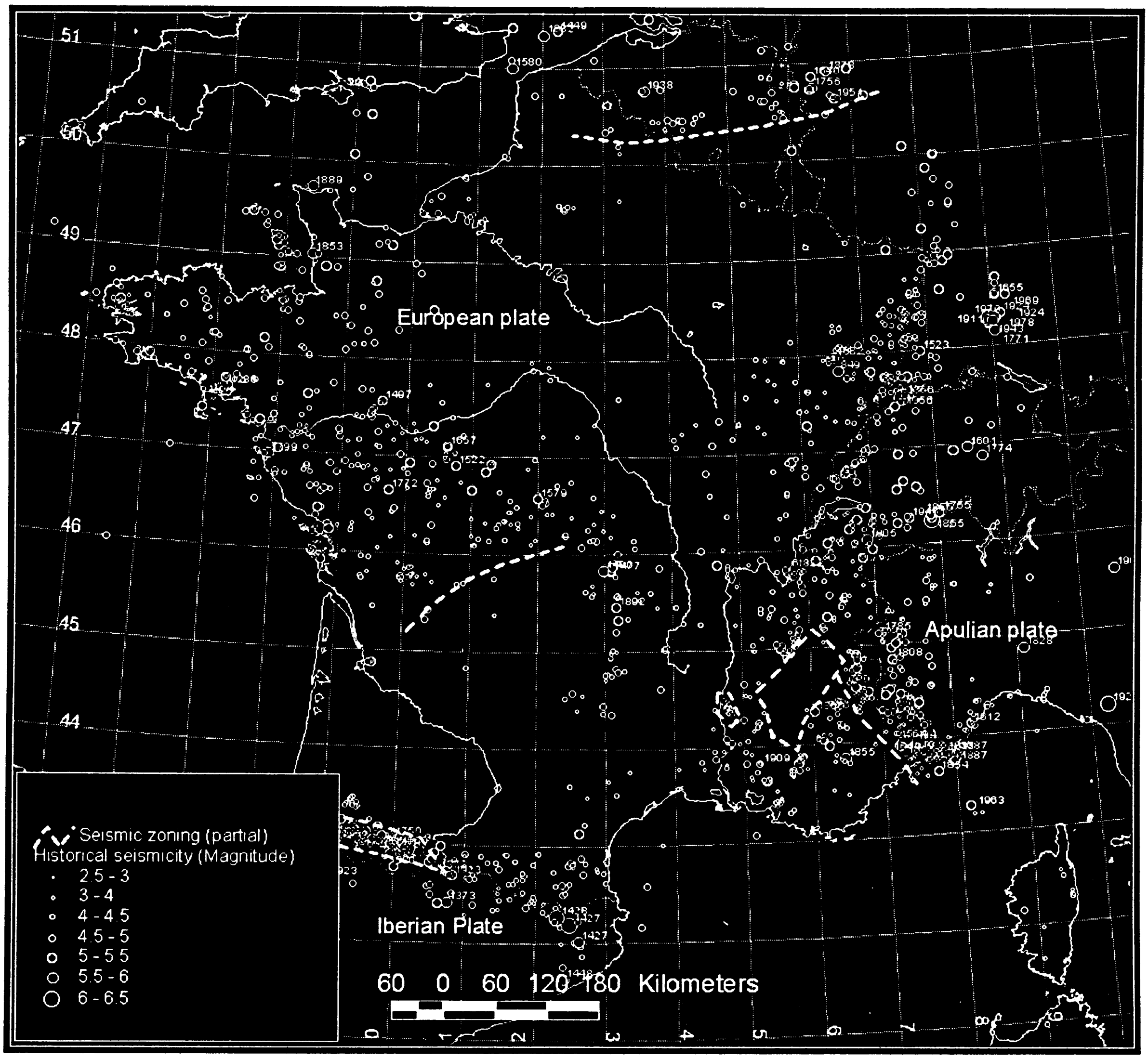

Figure 4: Partial seismic zonation.

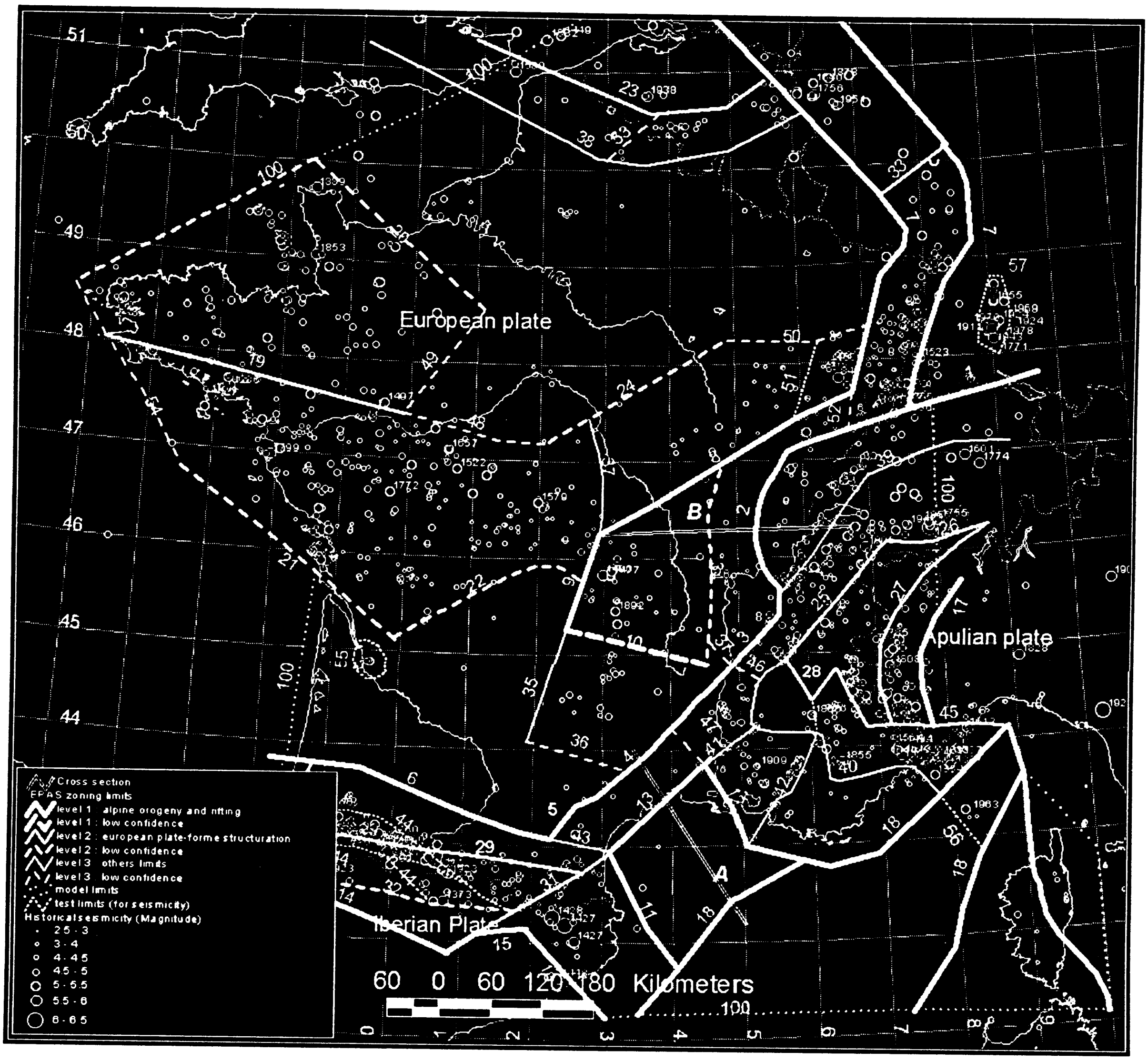

Figure 5 : Seismotectonic zonation for probabilistic approach.

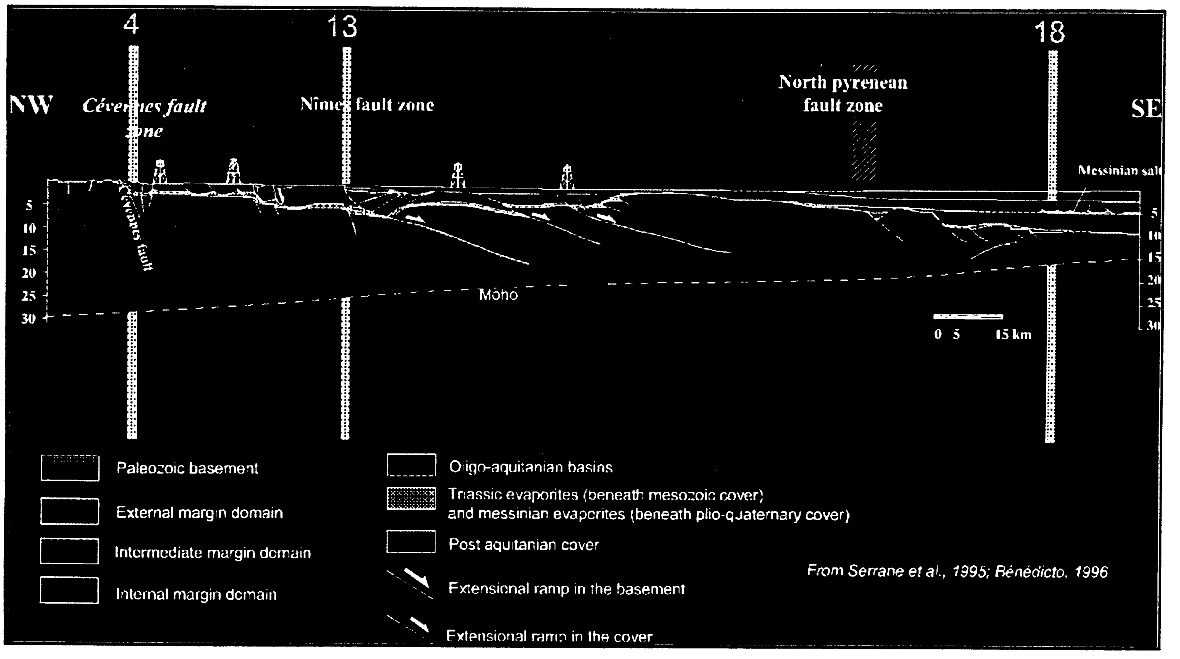

Figure 6 : Crustal scale cross section of the Cevennes -Nîmes fault system and Gulf of Lion area.

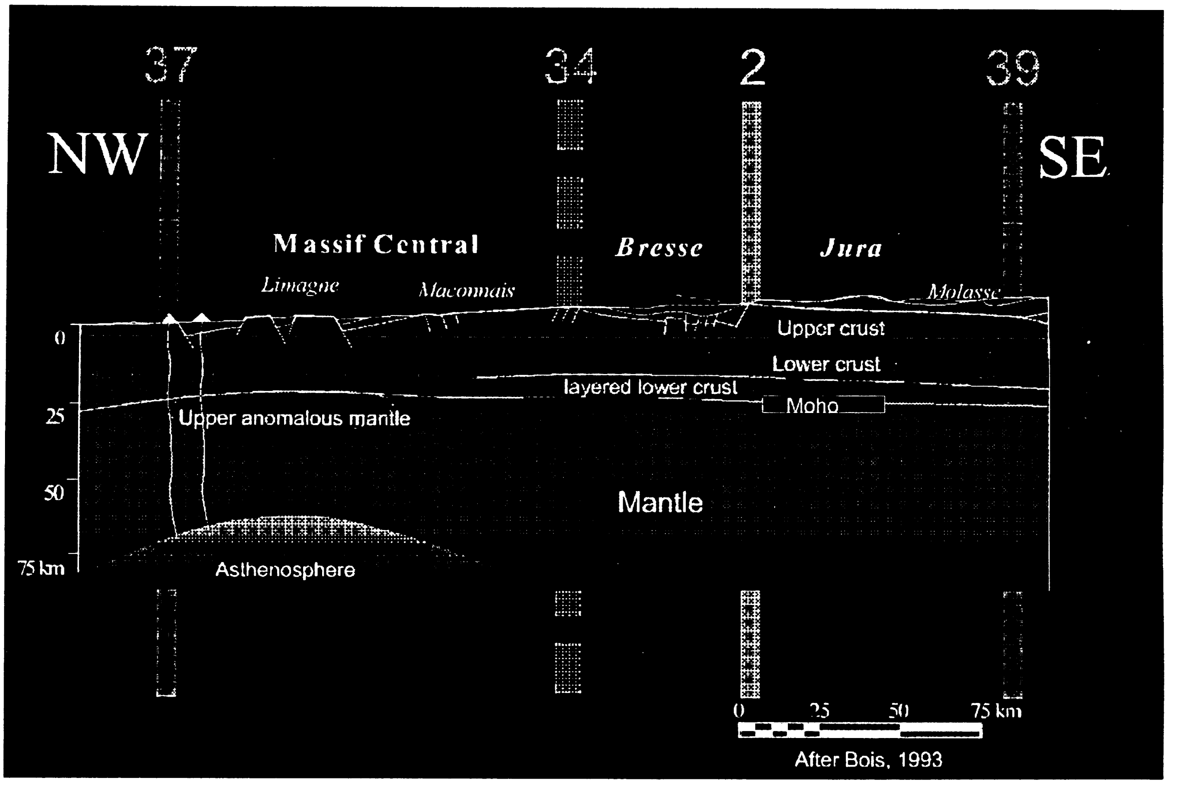

Figure 7 : Massif Central to Jura crustal cross section.

Table 1 : Identification of the zonation limits

Level 1 - Alpine structuration	
I : Major limits	1 : External limit of alpine deformation. 2 : External limit of western Jura thrust front. 3 : Prealps limit(Valence basin and lower-Dauphiné basement). 4 : Cévennes fault. 5 : "Corbières" limit - Aquitain basin. 6 : Nothern limit of pyrenean deformation.
II : European rifting	A : Fossé Rhénan - Massif Central rifting 7 : Upper rhine graben limits. 8 : Northern border of the Moho anticline. 9 : NW limit of Massif-Central extension zone. W limit of thermal anomaly, W limit of crustal thinning. This limit takes place east of the Sillon houiller. This structure is considered in order to take into account earthquakes of the Massif Central. 10 : Horizontal gradient of crustal thinning. Superimposed on the NW-SE fault network. Limits 8 to 10 surround the Massif Central thermal anomaly. B : Rifting of the Golfe du Lion. 11 : Catalan transfer zone. 12 : Arlesian tranfer zone. These two limits define the extensive basin of the oligo-miocene. 13 : Nîmes fault (decollement between cover and basement in passive margin context, about 6 kms uplift of the mantle in the pyrenean zone). 18 : Crustal thinning limit and miocene diapirs, intermediate to thin crust (10-15 km) and oceanic crust.
III : Alpine convergence	C : Pyrenean collision domain 14 : South pyrenean front. 15 : Valfogona thrust (Pedraforca). 16 : Valez graben limit. Compressive deformation limit including seismicity, east limit of non-strained Ebre. D : Alpine collision zones 17 : "Liguro-piémontaise" zone.
Level 2 : hercynian heritage	
Strong influence of hercynian structural network, reactivated when structures are favorably oriented w.r.t. stresses	
I : European plate-forme	19 : "Landes de Lanveau" axis, northern border of the "sud-armoricaine varisque" zone and southern border of the "centre-armoricaine" zone - this limit is situated north of the "Landes de Lanveau" axis 20 : Seismicity limit, trend of gravimetric and magnetic anomalies axis. Variscan granites in the upper part of the "centre-armoricaine" zone. Root of the variscan front (ECORS cross section, Matte, 1986) 21 : Gironde Fault, seismicity limit, limit of large geophysical anomalies, limit of internal variscan thrust sheet zone. 22 : Fault network cross-cutting basement structures in a left lateral sense. 23 : Limit of cambrian terrane thrusted over the Braban platform. The faulted zone corresponds to a basement horst. Variscan front to the north Rapid uplift to the north. 24 : Tonnerre structure indicated by geophysical signature. This structure is overlain by a thin mesozoic cover. It is cross-cutted to the NE by the Bray-Vittel fault and displaced left laterally by N-S Loire fault in the Sancerre region.
II : Alps and Pyrenees	25 : Frontal limit of external cristalline massifs thrusting (surrounding

	"piemontaise" zone and external cristalline massifs)
	26 : Spoon shaped low angle: Simplon and Insubrian faults.
	27 : Overthrusting of high pressure zone on "shistes lustrés" and ophiolites zone.
	28 : Limit of the "briançonnaise" zone and flyschs nappes, the SW border is the external alps limit.
	29 : North pyrenean fault.
	30 : Elizondo transform fault.
	31 : "La Têt" fault (oligocene extension limit).
	32 : Root of basement thrusting on Ebre, root of southern nappes, shallow seismicity and the root level.
III : Supplemental Limits	33 : Hunsrück fault crossing the Rhine massif, limit between transtensive deformation of upper Rhine graben and extensive deformation of lower Rhine graben. Also, the limit between oligocene extension to the south and miocene extension to the north. This feature displaces the Moho limit.
	34 : Limit of crustal thinning in eastern part of the Massif Central, surrounding the Limagnes domain.
	45 : Thrusting of the Moho and nothern limit of the ligurian flysch
Level 3 : poorly identified limits	
	35 : Villefranche de Rouergue fault: volcanism and lightly thinned crust to the east, no volcanism to the west.
	36 : Similar limit
	37 : Loire fault
	38 : Artois fault - south-Condroz fault
	39 : "Préalpes"- molassic basin»
	40 : Southern subalpine front
	41 : Nîmes fault ("subalpin" basin limit)
	42 : Durance fault
	43 : North pyrenean thrusting (Corbières)
	44 : seismicity limit : Bigorre fault to the south
	45 : Moho thrusting in franco-italian alps
	46 : Northern limit of southern subalpines domain
	48 : Seismicity limit
	49 : Seismicity limit
	50 : Vittel fault
	52 : W limit of the upper Rhine Graben
	53 : W limit of the Mons basin
	54 : Model limit
Limit to be tested (seismic zonation on cluster)	
	51 : Seismicity limit , Remiremont zone
	47 : Southern limit of Tricastin cluster
	55 : Bordeaux cluster (arbitrary border)
	56 : Ligurian source zone (high seismicity rate level)
	57 : Souabian Jura source zone
Model limits	
	Imposed spatial limits
	100 : Model limits

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