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Evidence for short-scale stress field variations within intraplate central-western France

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SUMMARY

Refinement of the seismicity distribution (4574 events) in western and central France, has been done by synthesis of seismological bulletins. Earthquakes have then been relocated by joint hypocentre and velocity structure inversion. The new hypocentre distribution indicates that the seismicity of those regions is much less diffuse than previously thought, mainly with regard to the depth distribution. The hypocentre improvement allows us to compute 44 new focal mechanisms and to revise bibliographic focal mechanism solutions. Then, the regional stress field was determined from 119 available focal mechanisms. It is characterized by a regionally significant strike-slip regime with NW-trending σ_1 . However, the refinement in location and increasing available focal mechanism solutions allow us to show that this strike-slip regime is overprinted by local extensional perturbations in three distinct areas. In the Massif Central, the Sillon Houiller, a ancient vertical shear zone, appears to be acting as a passive boundary between a western unit and an eastern unit that is uplifted by the ascension of a hot mantle plume at the base of the lithosphere. Extension is unexpectedly observed in the southern Armorican Massif (SAM), as well as in northwestern Massif Central. One can observe a good relation between the observed perturbed zones and lateral variation of Pn anisotropy in the mantle. This correlation and the scale of these areas are arguments in favour of a lithospheric process as the origin for the stress characteristics. We believe these extensional perturbations could be related to the anticlockwise rotation of the Iberian microplate and/or incipient subduction in the Bay of Biscay.

Key words: focal mechanisms, France, intraplate stress field, relocation of earthquakes, seismotectonics.

1 INTRODUCTION

Western Europe is usually recognized as a stable intraplate region characterized by a low strain rate resulting from far field stress, originated by Europe–Africa convergence and by ridge push from the Mid-Atlantic ridge (Grünthal & Stromeyer 1992; Müller *et al.* 1992; Gölke & Coblentz 1996). However, earthquakes sometimes occur in this region, outside the recognized seismogenic zones, that include the European Cenozoic rift system (Rhêne valley, Limagne graben, Rhine graben...) or orogenic regions as the Alps and the Pyrenees (Fig. 1). Recent intraplate earthquakes include a $M_L =$ 5.1 event, which occurred on 1990 April 2, on the English–Welsh border (Ritchie *et al.* 1991), and three events in western France: a 1972 September 7 event in Oleron (magnitude $M_L = 5.2$), a 2001 June 8 event in Vendée (magnitude $M_L = 5.1$) and finally an event on 2002 September 30, located in SAM, of magnitude $M_L = 5.7$. To understand the occurrence of these earthquakes, it is necessary to have an accurate image of the regional microseismicity as well as constraints on the regional stress regime. The focus of the current study is twofold: (i) to improve the resolution and to upgrade the image of the seismicity in central and western France (Fig. 1); (ii) to determine the stress field throughout the study area.

Because this part of France is characterized by low and diffuse seismicity, seismotectonic studies are rather scarce (Nicolas *et al.* 1990; Delouis *et al.* 1993; Amorese *et al.* 2000). Using a seismicity catalogue that we built including arrival times from 1962 to 2002, we refined the location of the events that occurred in the Massif Central, Charente region and Armorican Massif (Fig. 2). Thanks to the computation of regional velocity models, we mainly improved the determination of the focal depths.

It is well known that fault plane solutions of local earthquakes based on *P*-wave first motions strongly depend on correct identification of wave arrivals in the seismogram and on reliable estimates of the take-off angle of the rays at the source. Therefore, revised



Figure 1. Geological setting of the study area (rectangle). Grey shaded areas in the Massif Central correspond to Cenozoic and Quaternary volcanoes. SHF: Sillon Houiller fault, SASZ: South Armorican shear zone, NASZ: North Armorican shear zone, QFZ: Quessoy fault zone, MFS: Mayenne fault system. AE: direction of the Africa–Europe convergence, RP: direction of the Mid-Atlantic ridge push, AEPB: Africa–Europe Plate boundary.

locations helped us to constrain better the computation of 44 new focal mechanisms and to revise some bibliographic focal mechanism solutions. The synthesis of these solutions and previously published mechanisms, allowed us to define the stress field, by inversion of focal mechanism solutions, using the method of Carey-Gailhardis & Mercier (1987, 1992). We observed a regionally significant strikeslip regime with a NW-trending σ_1 , overprinted by three local extensional perturbations. In this paper, we do not discuss the detailed interpretation of the seismological patterns, but we focus our study on the determination of the regional stress field. A reference map for the stress determination of western Europe was published by Müller et al. in 1992. On the basis of this data set, Müller et al. (1997) interpreted the existence of perturbation zones as the coexistence of different crustal blocks with distinct stress regimes. However, the region we study was poorly constrained. Consequently, our work brings new data, allows us to refine the image of the perturbed regions and to discuss the hypothesis of crustal blocks proposed by Müller et al..

2 GEOLOGICAL SETTING

West-central France is a slowly deforming intraplate region. It is composed of two Hercynian massifs, the Massif Central and the

Armorican Massif, separated by two great Mesozoic sedimentary basins, the Paris basin and the Aquitaine basin (Fig. 1). In the east, the Alps are separated from the Massif Central by the Rhêne valley, which is part of the European Cenozoic rift system (as well as the Limagne graben). In the west, are the passive margins of the Atlantic ocean and the Bay of Biscay. The opening of the Bay of Biscay, beginning 114 Ma (Montardet et al. 1979; Olivet 1996), and now its closure by early stage subduction (Ayarza et al. 2004), together with the Pyrennean range separates the Iberian microplate from the European Plate. Synchronous to the development of the Cenozoic Limagne graben, volcanism occurred in the Massif Central but no volcanism has occurred west of the Sillon Houiller fault (SHF). This area is still potentially active as the youngest volcanoes are 7000 yr old (Nehlig et al. 2001). Several studies show a hot thermal anomaly beneath the Massif Central (Froidevaux et al. 1974; Vasseur 1982; Granet et al. 1995a; Sobolev et al. 1996), associated with a mantle plume, whose origin is still debated (Merle & Michon 2001). The major faults of the Massif Central and the Armorican Massif are the SHF and the South Armorican shear zone (SASZ). The French Hercynian massifs are mainly composed of granitic and metamorphic rocks. The Paris and Aquitaine basins are composed of quasi-undeformed, unmetamorphosed sedimentary rocks. They have a maximum thickness of 3000 and 10 000 m



Figure 2. All epicentres (black dots) of the study area. Rectangles enclose the Massif Central, the Charente region and the Armorican Massif subregions. Grey stars are the seismic stations of the LDG network and grey triangles are the stations of the ReNaSS network.

respectively and their basement is of the same nature as the surrounding massifs.

3 SEISMICITY DISTRIBUTION

3.1 Location procedure

3.1.1 Building of the catalogue

4574 events have been recorded from 1962 January 1 to 2002 January 1 in the study area, by the *Laboratoire de Détection Géophysique* (LDG) network and, since 1980, by the French National Seismic Network (Réseau National de Surveillance Sismique, ReNaSS). The catalogues of these two institutes, along with some data of the European–Mediterranean Seismological Centre (CSEM) have been combined month by month, from 1962 January to 2001 December. The data from CSEM include data from the British, Irish, Spanish, Portuguese, Belgian and Swiss networks.

As a first step, we located all the events using a code written at LDG (hereafter called FUSION), which considers both Pn and Pg phases (and corresponding Sn and Sg phases). The LDG was created in 1960 and, because at this time there were few seismological stations available, the seismologists of this institute identified both Pn and Pg phases (and associated Sn and Sg phases). This procedure allows the number of arrival times to be doubled and an additional constraint to be brought to the event depth determination through the (Pn-Pg) arrival times difference. This picking procedure is still used by LDG, despite the densification of the network, whereas conventional routines such as HYPO71 (Lee & Lahr 1975) only takes into

account one *P*-wave first arrival time and one *S*-wave arrival time. The FUSION algorithm is classically based on the Geiger method (Geiger 1910). Only origin time, epicentral latitude and longitude are inverted from the matrix of arrival times. The depth is used as a parameter in the traveltime computation and the final depth value (tested at a step size of 1 km) is the one that provides the best statistical results (in term of the rms of arrival times and axes of the true confidence ellipse). The locations are performed with all the available stations (Fig. 2) and the LDG 1-D crustal velocity model (M0 in Table 1a), a simple model appropriate for wide areas across France.

We compared this location procedure with the standard HYPO71 solutions. As microseisms are only detected by the closest stations, only the direct Pg and Sg are available so the results are identical. For larger magnitude events, recorded at long-range distance, we verified that FUSION brings generally more stability than HYPO1D in the hypocentral determination. This is particularly true for events of western Britanny, which are located with sparse regional distance stations. Corresponding seismograms depict energetic Pg and Sg waves, whereas Pn and Sn are very attenuated along these particular ray paths. In this case, automated picking, which works well for the first P arrival, would deal with misidentification and erroneous locations.

On Fig. 2, the seismicity of the northern Massif Central, the Armorican Massif and the Charente region is displayed. The seismological stations correspond to triangles (ReNaSS) or stars (LDG), whereas black dots are the epicentre locations. So, the first step of the work presented here was the building of a complete and reliable catalogue of uniformly located hypocentres for the whole studied region, with local magnitude from 2.0 to 5.7.

Table 1a. M0 model: starting model derived from the very simple model used in FUSION code. WMC0: the *a priori* model chosen as a starting model. It is deduced from Zeyen *et al.* (1997), for crustal velocities and from Juhenderc & Granet (1999) for the *Pn* velocity. WMC1: the final model deduced from VELEST, with WMCO model, as the starting model. WMC2: the final model generated by the convergence of the inversion of 50 random initial models.

Ν	40	WM	4C0	WN	1C1	WM	IC2
Depth	Vp	Depth	Vp	Depth	Vp	Depth	Vp
-2.5	3.5	-2.5	5.5	-2.5	3.5	-2.5	3.5
0	3.5	0	5.95	0	5.4	0	5.98
1	6.03	1	5.95	1	5.9	1	5.9
4	6.03	4	5.95	4	6.0	4	6.0
8	6.03	8	6.05	8	6.05	8	6.02
12	6.03	12	6.10	12	6.15	12	6.20
15	6.03	15	6.30	15	6.20	15	6.20
20	6.03	20	6.40	20	6.35	20	6.20
26	8.10	25	6.60	25	6.35	25	6.38
30	8.10	30	8.00	30	8.16	30	8.15

Table 1b. The same for CHP and LIM velocity models.

CH	PO	CH	P1	CH	IP2	LI	M0	LII	M1	LIN	12
Depth	Vp	Depth	Vp	Depth	Vp	Depth	Vp	Depth	Vp	Depth	Vp
-2.5	3.5	-2.5	3.5	-2.5	3.5	-2.5	3.5	-2.5	3.08	-2.5	3.62
0	5.0	0	5.07	0	5.45	0	4.06	0	3.92	0	5.14
2	5.5	2	5.72	2	5.80	2	5.57	2	5.91	2	5.92
4	5.6	4	5.87	4	6.05	4	5.70	4	6.00	4	5.92
8	5.9	8	6.06	8	6.15	8	6.0	8	6.02	8	6.05
12	6.1	12	6.10	12	6.20	12	6.10	12	6.43	10	6.22
15	6.3	15	6.10	15	6.43	15	6.10	15	6.50	15	6.62
20	6.4	20	6.54	20	6.71	20	6.35	20	5.50	20	6.62
25	6.5	25	7.09	25	6.97	25	8.10	25	7.30	27	7.35
30	7.7	30	7.22	30	7.20	30	8.10	30	7.80	30	8.00

Table 1c. The same for CHAR velocity models.

CHA	AR0	CHA	AR1	CHA	R2
Depth	Vp	Depth	Vp	Depth	Vp
-2.5	3.03	-2.5	3.04	-2.5	3.03
0	3.50	0	4.04	0	4.70
1	5.50	1	5.83	1	5.88
5	6.03	5	5.83	5	5.97
10	6.03	10	6.11	10	5.97
15	6.03	15	6.11	15	6.20
20	6.03	20	6.66	20	6.50
25	6.03	25	6.90	25	6.50
30	8.10	30	8.00	30	8.00

3.1.2 Relocation of the events

Our second aim was to improve the hypocentral location of the events using a more realistic velocity model. We did this by dividing the area into subregions in order to take into account their geological differences and the geometry of the network.

In some areas, where the number of events and the distribution of seismological stations allowed, we relocate the seismicity using a technique of simultaneous determination of the velocity model and the earthquake hypocentres (Ellsworth 1977). The main task of this method is to minimize the errors resulting from both the model parameters and arrival times. We relocated these regional groups of events through the application of the program VELEST written by Kissling *et al.* (1984), which allows us to invert the minimum 1-D model with station corrections and hypocentre parameters, which minimizes the rms residual of the full data set.

For each area, we selected the best events, that is to say those with the highest quality arrivals (axes of the confidence ellipse smaller than 10 km, as computed by FUSION; with at least seven stations) and that cover the entire area under consideration.

VELEST uses only one P and one S arrival time and, with the intention of this being a regional-scale study, we only used stations at less than 200 km epicentral distance. We used Pn and Sn for the regional-distance stations and kept Pg and Sg phases for the closest stations. Therefore, we favoured the use of Pg and Sg phases but kept enough Pn and Sn to determine Moho depth and velocity.

The determination of this minimum 1-D model is a trial and error process, which starts with an *a priori* velocity model. Our initial models (that we call model 0, in the following discussion) were based preferably on refraction seismic profiles, as recommended by Kissling *et al.* (1994).

We first computed final models (the so-called model 1), by conducting a series of successive 1-D inversions and relocations, in order to minimize the final global variance of our set of location data.

In a second step, we conducted a grid search of the *a priori* 1-D model, by introducing random changes of layer velocities (≤ 1 km s⁻¹) in the updated *a priori* model (model 1). A plot of the velocity models resulting from the inversions allows us to show that these models converge towards an average model (model 2) and provides knowledge of the variations of resolving power with depth. The aim of this procedure is to verify the stability of the results considering both the final minimum 1-D model and location parameters.

3.1.3 The depth of the events

Some general comments about depths can be made. In the Massif Central and Charente regions, most earthquakes are shallow (depth



Figure 3. Example of inversions for a 1-D model for the CHP area. (a) The initial model CHP0 is deduced from seismic results shown by bold, grey dashed line, the inverted model CHP1 is the bold black line and the initial random models generated from CHP1 model are thin dashed lines. (b) At the end of the inversion process, the resulting models are the thin dashed lines. The convergence of the velocities around a single model CHP2 is shown by the bold line and consequently chosen as the best minimum 1-D model. The grey line corresponds to CHP1 (the resulting model after the first iteration).

 \leq 8 km), nevertheless, they are all located in the basement Hercynian rocks. The seismogenic crust has a thickness of 11 ± 1 km (Fig. 3). No discrepancy is observed between the shallowest and the deepest focal mechanisms. Moreover, the small topographic variations of this area cannot be invoked for any stress variation with depth. Thus, we consider that these earthquakes testify to the style of faulting in this area. Indeed, these focal solutions are consistent with the over-coring data from Cornet & Burlet (1992) that show a rotation of σ_{Hmax} towards the E–W in the eastern Massif Central (EMC). Reliability of hypocentral determination in the Armorican Massif is not good enough to allow detailed interpretation of the revised depths of the earthquakes. Nevertheless, considering only the strongest and best located events, the seismogenic crust seems to be 12 ± 1 km thick.

3.1.4 The Massif Central

In the Quaternary volcanic Massif Central, 2292 events are clustered in tectonically active areas: along the volcanic area, near the Limagne graben and where the SASZ ends. So, we divided this area, into three subregions (Fig. 3). They are the so-called western Massif Central (WMC), the Chain of Puys (CHP) and the Limagne region (LIM). First, we chose the three models WMC0, CHP0 and LIM0 to be applied in the three studied areas, on the basis of the seismic refraction results from Zeyen *et al.* (1997). These models are given in Tables 1(a) and (b). Then, we followed the procedure described above : first, we computed three models WMC1, CHP1 and LIM1 (Tables 1a and b). We conducted a grid search of the *a priori* 1-D model, by introducing random changes of layer velocities ($\leq 1 \text{ km s}^{-1}$), in the WMC1, CHP1 and LIM1 models. Fig. 3(a) dis-

plays an example of random initial models, for the CHP area, around the inverted model CHP1. Fig. 3(b) shows the convergence of velocities around a single model, CHP2, close to the model CHP1. Nevertheless, the 1-D model is less resolved at depth >20 km than for the shallower layers. This model was chosen as a new starting model in a new inversion sequence to obtain the final locations. Table 1 presents the starting and final velocity models obtained by inversion, then the final minimum 1-D model we determined for each area.

Strictly speaking, the minimum 1-D model deduced from this study does not represent a true geophysical image of the studied areas. It consists of an average velocity model in the medium crossed by the rays from the hypocentral zone to the stations, which is deduced from a trial and error approach using an earthquake and station data set. However, in this study, we selected only stations that are close to the epicentre area. Consequently, the best minimum 1-D model obtained can be evaluated in terms of the regional structure. We can observe that all the inverted CHP and LIM models tend to have a low-velocity layer at the bottom of the model (Fig. 2), still lower than the anomalous low velocity obtained by seismic refraction for the upper mantle (Table 1b). Controversially, models computed for the WMC area are characterized by rather homogeneous and high crustal velocities. Note that, the final minimum 1-D models are very close to the results obtained by Juhenderc & Granet (1999) using anisotropic tomographic modelling beneath France. Their tomographic image of Pn velocity perturbation clearly shows high *Pn* velocities, up to 8.15 km s⁻¹ in the west of Massif Central, whereas, crossing the SHF (Fig. 1), the Pn velocity decreases dramatically down to 7.66 km s⁻¹. This low-velocity region coincides with the main volcanic areas and these low velocities are associated

 Table 2. Data and model variances for the 1-D models. Initial data variances were measured after the first relocation by VELEST using the starting model.

 The final variance are results from six iterations of the direct inversion with the final velocity model.

	Number of located events	Initial variance (s^2)	Final variance (s^2)
МСО	454	0.59	0.37
CHP	455	1.23	0.43
LIM	304	1.21	0.74
CHAR	541	1.98	0.66

with the high temperature related to the Neogene volcanic activity (Sobolev *et al.* 1997). We also find low Pn velocity beneath the Limagne graben, as already obtained by Perrier & Ruegg (1973) from refraction results.

Table 2 shows the improvement in the variance obtained during the procedure. In Fig. 4 we present the comparison between 1242 hypocentre locations performed in the first part by FUSION and in the second part by VELEST. The epicentral parameters are similar and preliminary ill-located events are rather scarce. Nevertheless, the relocated events tend to be more clustered and orientated closer to the direction of geological structures. However, the projection of hypocentres along two vertical cross-sections, allows us to show the main differences between the two series of results. The focal depths are dramatically shifted. The seismogenic zone is limited to 10 km depth and the hypocentres are more clustered, as shown on the two vertical cross-sections. Furthermore, we verified that the change of velocity models (as explained in Section 3.1.2) did not imply dramatic change of focal depth. From comparison between the different locations obtained with VELEST, we deduced the maximum uncertainties in depth are ± 1 km.



Figure 4. Comparison of epicentres and hypocentres of the Charente region and Massif Central located with the M0 model (Table 1a), shown as circles, and relocated by the joint velocity-velocity model inversion (black triangles). Hypocentres are displayed on two east-west cross-sections, at 45.1 and 46.0 latitude north. Hypocentres plotted lie within 15 km of the cross-section lines. SASZ: South Armorican shear zone, SHF: Sillon Houiller fault.

A detailed interpretation of the seismological patterns is beyond the scope of this publication and will be the subject of a separate article (Mazabraud *et al.* 2005).

Therefore, the VELEST code allows us to find realistic crustal models that can be now used for the location of the local seismicity. They allow us to constrain the focal depth better than the 1-D average velocity model of Table 1(a) (M0).

3.1.5 The Charente region

981 events are recorded in the region. The 1972 Oleron Island swarm, in the centre of the area, clearly contrasts with the surround-ing more diffuse seismicity (Figs 2 and 4).

Without available refraction data, we began with a simple velocity model derived from the one already used in the location process with FUSION (M0, Table 1a), but with more layers, in order to obtain a better inverted minimum 1-D model that fits the data set [model CHAR1; then CHAR2 (Table 1c) obtained with the procedure previously described]. The azimuthal coverage of the stations is limited to $180^{\circ}-200^{\circ}$. So, this velocity model has no geological significance and the procedure only allows us to compute station corrections and to obtain joint hypocentre locations. Once again, the variance is improved (Table 2). The main change in hypocentres (Fig. 4) still relates to the depth of the events, which consistently deepens from west to east.

3.1.6 The Armorican Massif

The peninsular shape of the Massif provides poor azimuthal coverage by the networks and most of the events were only recorded by regional-distance stations. Therefore, the relocation methodology could not be applied for this westernmost region. We only benefit from the FUSION location catalogue, which provides rather numerous seismic events (1301 events) for this region. The dispersion of the seismicity (Fig. 2) is partly the result of the poor azimuthal coverage. Moreover, the focal depths are usually not constrained. Nevertheless, the largest magnitude events ($M_L > 4.0$) are recorded by British and Spanish stations and produce more reliable locations. Since 1996, installation of stations in Brittany (Fig. 1) allows a significant improvement in location.

4 FOCAL MECHANISMS

Taking into account the improvement in the epicentral coordinates, mainly in hypocentral determination and in the velocity model, we can compute more realistic take-off angles to determine new focal mechanism solutions.

4.1 New Earthquake fault-plane solutions

Focal mechanisms have been computed by means of the FPFIT code (Reasenberg & Oppenheimer 1985), which systematically searches the solution space for the double-couple fault plane solutions that best fit, in a least-squares sense, a given set of observed first-motion polarities. This method may determine several solutions with related uncertainties for both nodal planes. For the best-constrained mechanisms, only one solution is obtained.

In the current study, we have determined 44 new earthquake focal mechanisms. The selected solutions are reported in Table 3 and shown in Fig. 5.

4.2 Previously published focal mechanisms

Focal mechanisms from other events that occurred in the studied region have already been published (Delhaye 1976; Santoire 1976;

Veinante-Delhaye & Santoire 1980; Nicolas *et al.* 1990). These authors used the LDG velocity model to determine the focal mechanism solutions.

We revised these solutions with the help of the new hypocentral determinations and velocity model. Some mechanisms have been computed with a majority of Pn polarities. In this case, the change of take-off angles is small, even with a shift of focal depth and a different velocity model. Some others, computed with many Pg polarities, are more sensitive to the focal depth and velocity model. All previously published focal mechanism solutions are reported in Table 4. Only eight events have clearly different solutions after revision. They are indicated by a star in Table 4 and are displayed on Fig. 5.

Dorel *et al.* (1995) and Amorese *et al.* (2000) computed focal mechanisms from dense local networks in Normandy and the EMC (Fig. 1), with realistic take-off angles. We used their solutions without revision.

4.3 Quality of the focal mechanism solutions

To each focal mechanism solution, a quality factor has been assigned. We took into account the error limits, as computed by FPFIT (strike and dip uncertainties: Δ STR, Δ DIP) and solution quality through a parameter *F*, which qualifies a data misfit measure) and the magnitude of the earthquakes.

Then, following Zoback (1992), we classified the available mechanisms into four classes (A–D).

A: $M_{\rm L} \ge 4$ and well-constrained solutions (Δ STR, Δ DIP <20° and F < 0.025).

B: $M_{\rm L} \ge 4$ and less constrained or $3 \le M_{\rm L} < 4$ and well constrained.

C: $2 \le M_{\rm L} < 3$ and well constrained or $3 < M_{\rm L} < 4$ and less constrained.

D: $M_{\rm L} < 2$ or poorly constrained solutions.

Only one exception was made for the focal mechanism solutions that we determined with local network data that can lead to reliable solutions even for magnitudes ≤ 3 . These solutions are classified as C.

4.4 Results

A synthesis of the previously published and newly calculated focal mechanism solutions for the Armorican Massif is plotted in Fig. 6(a). In the south, most mechanisms are characterized by a dominant normal-slip component and a NNE-trending *T*-axis, whereas in the north, the type of mechanism is less coherent, with E-trending *T*-axis in the northwest of the massif and nearly NE-trending *T*-axis northeast of the massif. In the southeast, only two mechanisms (n° 101 and n° 109) do not seem consistent with the other ones. They are more likely related to the mechanisms of the northeastern Charente region and northwestern Massif Central that show nearly NW-trending *T* axes.

Fig. 6(b) shows the new and the published focal mechanisms for the Charente region. Most solutions are compressional or strike-slip, with a NE to E trending *T*-axis. The seismic crisis of Oleron Island, that began in 1972 with a $M_L = 5.2$ event (n°82) and lasted more than 10 yr, is represented by five focal mechanisms (82, 83, 87, 88 and 91). However, they also have a normal component and n° 88 is purely extensional. Four of them are strike-slip. The $M_L = 5.2$ event (n° 37), of 2001 June 8, is located at 12 km depth, on the southeastern

Table 3. New	focal mec	hanisms. The	e focal mechanisms a	tre classified by d	late for eac	th geographi	cal region	ı. The s	tress field z	one is de	etermin	ed a post	eriori b	y stress	field inve	rsion.			
Geographical	Number	Stress field	Date	Time (UTC)	Long.	Lat.	Depth	Mag	Quality		Plane A			Plane E	~	P-a	xis	T-a	is
area		zone	(AYYY/MM/DD)	(HH/MM/SS)	(_)	(_)	(km)	(IMI)		Az	Dip	Vect.	Az	Dip	Vect.	P az.	P dip.	T az.	T dip.
Central Massif	-		1000/05/03		1500	10 254	007	0	þ	151	00	ç	0,0	ľ	001	E 0 F	11	7	ç
	- (CHMC	20/C0/6961 1000/07/0601	10-00-31	1 2016	400004	0.05	4.0 4 K	9 2	101	00 88		246	10	-178	207	11	304	0 L
	1 (1)	CHAR	1991/05/22	13:41:12	1.8231	46.3667	0.01	5.7		115	00 77	177	206	87	13	340	9	17	12
	4	CHAR	1991/05/30	9:15:26	1.8339	46.3577	5.00	3.3	В	134	53 -	-113	349	43	-63	346	71	240	ŝ
	5	CHAR	1991/06/09	0:34:04	1.8893	46.2808	5.00	3.5	В	112	81	177	202	87	6	337	9	67	9
	9	ECM	1991/06/27	4:44:12	2.9985	45.0944	1.87	3.4	В	120	60	-41	233	55	-143	85	49	177	7
	7	ECM	1991/07/28	1:54:25	3.2208	45.2356	0.18	3.4	С	241	76	141	342	52	18	296	15	195	37
	8	CHMC	1992/09/23	2:41:38	1.088	46.7871	1.46	3.2	С	30	34 -	-160	283	79	-58	226	46	348	27
	6	ECM	1993/09/02	3:13:46	2.986	45.0959	6.06	3.0	В	5		-120	241	37	-40	234	57	117	17
	10	ECM	1993/10/17	22:57:01	3.88	45.2492	1.10	3.6	С	148	88	145	239	55	2	197	17	100	20
	11	CHAR	1994/01/29	0:31:00	1.5688	46.6978	8.66	3.7	В	13	48	-54	146	53	-123	354	64	259	З
	12	CHAR	1994/12/18	2:56:01	1.4316	46.4011	4.70	3.0	С	139	85	-77	250	14	-159	63	48	217	39
	13	CHAR	1995/02/24	9:05:54	1.5624	46.599	0.91	3.2	C	21	85	20	289	70	175	153	12	247	19
	14	ECM	1995/05/11	23:10:07	3.8108	45.2633	3.32	3.1	С	121	86	138	215	48	5	177	27	68	33
	15	ECM	1995/05/14	6:45:59	3.0825	45.3027	0.63	3.2	В	11	87	-6	101	81	-177	326	2	56	7
	16	ECM	1995/07/30	10:13:21	3.6321	45.6134	0.44	3.1	D	211	66	119	338	37	43	281	16	162	59
	17	CHAR	1995/09/15	18:24:26	1.4997	46.3232	8.68	3.3	В	19	73	23	282	68	162	150	З	241	28
	18	CHMC	1996/06/25	5:10:13	1.0264	46.5184	3.61	3.4	В	30	- 92	-123	280	36	-25	264	48	145	24
	19	CHMC	1997/08/23	15:07:18	1.2515	465038	0.52	3.6	В	64	57	29	317	66	143	12	5	277	42
	20	ECM	1997/08/29	0:55:33	3.6343	45.5913	5.00	3.6	В	102	- 09	-122	333	43	-47	322	61	214	10
	21	CHAR	1997/11/14	23:52:02	2.1795	46.554	1.43	3.1	В	95	51 -	-157	350	72	-41	305	41	47	13
	22	ECM	1999/01/19	1:29:21	2.8067	45.9654	1.81	3.4	В	46	43	163	149	78	48	269	22	20	41
	23	CHMC	2000/05/06	13:33:04	1.4321	46.4934	5.00	3.3	В	252	79	-41	351	50	-166	204	35	307	18
	24	ECM	2000/07/13	1:50:47	3.0183	45.8877	9.25	3.3	В	28	65	09	262	38	137	140	15	255	59
	25	ECM	2001/05/29	11:10:02	3.5902	45.6212	7.84	3.1	В	223	73	-2	314	88	-163	180	14	87	10
	26	ECM	2001/11/05	8:53:13	3.7429	45.5787	5.75	3.4	В	101	34 -	-162	356	80	-57	299	45	60	28
	27	CHAR	2000/12/05	11:53:27	1.6207	46.3658	3.84	3.0	С	8	71	35	265	57	157	134	6	231	38
Charente Region									t		;	Î	0	į			;	10,	ļ
	87	CHIMC	1996/06/10	20:20:0	0.095/	40.9013	5.04	5.0 2.0	، ت	04 0	c :	0/-	188	C7 }	-145	0,	cc °	15/	17
	67	CHAR	1996/12/01	11:22:46	0.0269	1208.64	1.62	6.5 6 1	а.	65 1	00	43	187	90	15/	160	о ;	007	ς ζ
	50 12	CHAR	1007/00/20	1:24:16	-1.1405	40.334	9.89 5 00	0.4.0	A C	11	47	84 8	24/	00	171	615 201	10	707	70
	10 27	CHAR	05/60/1661	13:00:00	1260.0	46 0755	00.0	0.0	ل ر	1/1	10	113	210	00	-1/1	100	0 5	00 27	0 7
	33	CHAR	2000/02/23	15:46:47	0 3507	45 4155	00.C	4 1 0.0		=	79	40	017 017	<u>, r</u>	ر 166	136	F %	730	
	46	CHAR	2000/05/02	6:52:10	-1.9241	46.8519	0.51	3.0	: 0	89	60	43	334	54	142	210	2 4	305	20
	35	CHAR	2001/04/05	17:27:22	-0.1086	46.212	14.31	3.0	В	213	60	121	343	42	48	281	10	173	62
	36	CHMC	2001/04/30	15:44:55	0.8982	46.9053	2.35	3.0	В	35	51 -	-114	251	45	-63	241	71	142	б
	37	CHAR	2001/06/08	13:26:53	-1.0799	46.6625	11.76	5.2	A	123	86	139	216	49	5	175	22	73	28
Armorican Mass	if																		
	38	NAM	1996/11/26	20:21:37	-1.5227	48.6874	5.00	4.0	А	107	65	129	349	45	37	330	53	224	12
	39	SAM	1998/06/11	17:52:14	-2.8011	47.6879	9.86	3.2	С	55	56	27	309	68	143	4	7	268	42
	40	SAM	1999/03/20	3:01:30	-2.7934	47.6677	9.76	3.1	D	21	42	44	255	62	123	322	11	213	59
	41	SAM	1999/05/03	6:34:15	-4.1686	47.8722	5.00	3.6	В	28	51	143	273	62	-45	235	51	333	2
	42	SAM	2000/07/07	21:26:21	-2.7256	47.3735	0.47	3.0	С	84	28	-141	318	73	-68	257	57	31	24
	43	SAM	2000/12/05	0:41:10	-2.4996	47.9138	2.07	3.3	В	109	62	125	345	44	43	330	58	223	10
	44	SAM	2002/09/30	6:44:48	-3.2457	47.8640	10.90	5.7	A	4	46	-43	127	61	-127	345	57	243	8

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Figure 6. All focal mechanisms for the study area. Black (new focal mechanism) or grey (bibliographic focal mechanism) quadrants are compression, whereas white are dilatation. Grey stars are the seismic stations from the LDG network and grey triangles are the stations from the ReNaSS network. SASZ: South Armorican shear zone, NASZ: North Armorican shear zone, QFZ: Quessoy fault zone, MFS: Mayenne fault system, SHF: Sillon Houiller fault. (a) Armorican Massif, (b) Charente region, (c) Massif Central.

termination of the SASZ, a dextral strike-slip Hercynian ductile shear zone. In terms of the orientation of the *T*-axis, only a few focal mechanisms (N°: 28, 36, 89, 93) seem inconsistent with the other ones. Almost all are located in the northeast of Charente region and have a NW-trending *T*-axis, consistent with some mechanisms of the northwestern Massif Central. These mechanisms probably reflect a change in the stress field.

Fig. 6(c) shows the Massif Central, Charente and Armorican Massif focal mechanisms. We can observe that many focal mechanisms are concentrated in the northwestern Massif Central. This area is seismically more active than the southwestern Massif Central and EMC (Figs 2 and 4), with strong enough earthquakes ($M_L \ge 3.0$) to compute reliable focal mechanism solutions. The type of mechanism is variable; most mechanisms have an important strike-slip component and a NE-trending *T*-axis. In the southeastern Massif Central, 11 new focal mechanisms are presented. This area is characterized by a topographically high, north–south trending Quaternary volcanic range at 2.9 longitude east.

5 INVERSION OF SEISMIC SLIP-VECTOR DATA SET TO DETERMINE THE STRESS STATE

5.1 Methodology

To compute the stress states responsible for present-day activity (i.e. for earthquakes) in the studied area, we perform quantitative inversions of the earthquake focal mechanisms, using the method proposed by Carey-Gailhardis & Mercier (1987, 1992), which is one of several existing algorithms (e.g. Vasseur *et al.* 1983; Gephart & Forsyth 1984). For a robust data set these different algorithms yield similar results (Mercier *et al.* 1991). Both the detailed methodology and the stress axis uncertainties are extensively presented in Baroux *et al.* (2001). The confidence of focal mechanism solutions is taken into account by the help of a weight given to the data, according to its quality, in the inversion procedure.

Taking into account the fact that very small magnitude events can only represent localmation, we have introduced a weight with regard to the magnitude of events with focal mechanisms in our inversion. Our catalogue contains a significant number of events of magnitude higher than 4. We have verified that their focal mechanism solutions are in good agreement with the local stress tensor, inverted with the help of smaller magnitude events. Moreover, many other studies already point out that small magnitude events are generally responding to the same regional stress field as the largest events, thus we can statistically infer a good image of the regional stress field from them (Amelung & King 1997; Angelier *et al.* 2004).

5.2 Results

In the current study, we analyse 119 events including bibliographic (75, see references in Table 4) and new (44, Table 3) focal mechanisms. Delouis et al. (1993) directly inverted the polarities of 24 available earthquake focal solutions, from Nicolas et al. (1990) with the Rivera & Cisternas (1990) method. These authors determined the stress tensor of a wide area composed of the northern Massif Central, the Charente region and Armorican Massif. Nowadays, the densification of the seismic networks, together with the increased time of observation, allows us to compute reliable enough focal mechanism solutions, even for small-magnitude earthquakes ($M_{\rm L}$ > 3), and consequently permits us to examine smaller scale variations of the stress field. On the basis of the consistency of the focal mechanism T-axis orientations, we subdivide our focal mechanisms into five regionally significant data sets. These groups represent tectonic domains in which the stress field is expected to be rather homogeneous at the resolution allowed by our data. As all the events have been relocated, we have good confidence in the localization and correlation between the focal mechanism groups and the tectonic domains. Each focal mechanism located close to the boundary between two domains, and potentially compatible with both data sets, has been tested in each domain. It was then incorporated to the group with which it was the most compatible. During the inversion, a weight was given to each focal mechanism, according to its quality (Tables 3 and 4). The stress tensors computed by inversion of the focal mechanisms for the five areas are presented in Figs 7 and 8.

5.2.1 Western Massif Central (WMC) and the Charente region (CHAR)

For this zone, 46 mechanisms are available, including 18 new ones. Some bibliographic focal mechanism solutions are not well constrained because they occurred between 1976 and 1981, when the seismic networks were sparse. Thus, they were not used in the inversion. The inversion provides a well-constrained result, taking into account 38 out of 46 mechanisms, with more than 80 per cent of the (τ , s) angular deviation below 20° and 100 per cent below 30°. It gives a strike-slip regime (vertical σ_1) with a horizontal 152°NE-trending σ_2 (Fig. 7).

5.2.2 Eastern Massif Central (EMC)

In southeastern Massif Central, we compute 12 new focal mechanisms. New focal mechanisms, together with the revised published solutions, furnish a set of 29 data points. Previously calculated events, from 1991, are recorded by dense and homogeneously distributed networks. Consequently, most mechanisms are well constrained, even if some small-magnitude events do not provide reliable focal mechanism solutions. Our focal mechanisms have been inverted together with 12 mechanisms published by Dorel *et al.* (1995). Dorel et al.'s focal mechanisms correspond to small earthquakes, with magnitudes ranging from 1.8 to 3.0, but have been computed using data from a temporary local network. The resultant stress regime is extensional and characterized by a 236°NE-trending σ_3 . In a second stage, we combined this data set with the available focal mechanisms from the western Provence area, provided in Baroux et al. (2001) mainly around the Rhêne valley domain, at the southeast of the Massif Central. This combined data set of 34 mechanisms appears homogeneous (data being clearly compatible) and has been inverted. Some focal mechanism solutions are compressive and inconsistent with an extensional stress regime. Those solutions (e.g. n° 16) appear to be the less well constrained (see Tables 3 and 4) and are removed during the inversion process. This inversion leads to a reliable result, 21 focal planes out of 34 mechanisms were selected and more than 85 per cent of (τ, s) angular deviations lower than 20° (Fig. 7). These selected planes are consistent with a WSW-trending extension (69°NE- σ_3). In the following, we will refer to this last result (Fig. 7).

5.2.3 Northwestern Massif Central and northeastern Charente region (CHMC)

Northwest of the Massif Central and southeast of the Armorican Massif, the focal mechanisms are characterized by SE-striking *T* axes, clearly inconsistent with the neighboring general NE-striking T-axis orientation. Eleven focal mechanisms are available in this area, seven of which are new and relatively well constrained. The poorly constrained events were removed from the inversion. The final inversion takes into account seven focal mechanisms and yields a good quality result with all (τ , s) angular deviation below 10°. The stress tensor is extensional with a 130°NE-trending σ_3 (Fig. 7).

5.2.4 Southern Armorican Massif (SAM)

The Southern Armorican Massif (SAM) is characterized by the E-striking SASZ. Ten mechanisms, of which six are new, including the well-constrained 2001 September 30, $M_{\rm L} = 5.7$ Lorient event (Perrot *et al.* 2005), have been inverted. The inversion result is of good quality and 7 of 10 mechanisms are well explained by the resulting stress field [all (τ , s) angular deviation below 5°]. The stress tensor corresponds to an extensional stress regime and suggests a dominant normal-faulting regime with a non-trivial strike-slip component (Fig. 7). Some focal mechanism solutions are incompatible with extension (ex: n° 40). As in the other extensional zones, they are the less well constrained solutions (see Tables 3 and 4).

5.2.5 Northern Armorican Massif (NAM)

In Normandy (northeastern Armorican Massif), a regional network allowed Amorese *et al.* (2000) to publish reliable focal mechanism solutions for small-magnitude earthquakes. These focal mechanisms have been inverted together with newly computed solutions and revised older mechanisms (Nicolas *et al.* 1990).

Throughout the northern Armorican Massif (NAM), 13 of 19 focal mechanisms provide a reliable inversion with all (τ , s) angular deviation below 20° (Fig. 7). The resultant stress regime appears to be complex, as the principal stress axes are not horizontal or vertical. We interpret this result as a stress field arising from the interaction of a dominant strike-slip regime and the attenuation of the extensional perturbation of the SAM.

Table 4. Bibli	ographic f	ocal mechan	isms. The focal mect	anisms are class	sified by	date for	each ge	ographi	cal region.	The str	ess fiel	d zone i	s detern	nined a	posterio	ri by stre	ss field in	version.		
Geographical area	Number	Stess field zone	Date (YYYY/MM/DD)	Time (UTC) (HH/MM/SS)	Long. (°)	€) (°)	Depth (km)	Mag (MI)	Quality	Az	Plane Dip	A Vect.	Az	Plane Dip	B Vect.	P-a P az.	xis P dip.	T az.	xis r dip.	Ref. R.
Central Massif																				
	45	CHAR	1968/04/07	19:13:23	1.29	46.21	7.5	4.0	A	14	85	125	111	363	6	316	40	76	31	2
	46	CHAR	1975/04/13	4:56:29	1.66	46.25	12.0	3.5	В	10	89	0	100	84	180	325	5	55	З	7
	47	CHAR	1976/05/20	3:15:38	1.35	46.44	2.0	2.9	С	160	68	57	40	39	143	274	17	28	55	2
	48	CHAR	1976/08/18	16:02:54	1.72	46.69	14.0	3.1	В	0	58	105	155	35	67	310	73	81	12	2
	49	CHMC	1976/10/22	18:46:27	1.32	46.69	7.0	3.5	C	265	53	64	124	44	120	13	5	115	69	2
	50	EMC	1977/04/27	23:25:20	2.93	46.52	3.0	4.1	A	141	90	180	51	87	0	9	2	276	2	2
	51	CHAR	1977/04/29	18:15:03	1.02	45.63	9.0	3.2	C	27	53	68	241	42	117	133	9	240	72	2
	52	CHAR	1977/06/30	2:57:15	1.45	46.31	10.0	3.1	C	90	50	84	280	40	98	319	83	185	5	2 *
	53	EMC	1978/02/11	14:13:13	3.25	46.34	15.3	4.1	A	123	90	0	213	90	180	348	90	258	90	2
	54	EMC	1978/03/30	17:33:39	3.43	46.29	5.0	3.3	C	20	35	19	94	79	123	158	27	38	45	1
	55	EMC	1978/05/25	18:13:31	3.99	46.71	0.1	3.2	C	5	90	0	95	90	180	140	0	50	0	1
	56	EMC	1978/08/29	22:23:48	3.29	43.69	8.0	4.1	В	32	57	-80	230	34	-105	272	76	129	12	2
	57	CHAR	1978/09/03	3:51:36	1.30	46.32	5.0	3.1	C	90	50	80	285	41	101	308	81	187	5	2
	58	CHAR	1978/11/06	10:48:24	1.01	45.70	12.0	4.4	A	74	43	150	187	70	51	305	16	54	49	2
	59	CHAR	1979/05/11	18:06:25	1.03	45.64	13.4	3.5	C	0	89	0	90	84	180	315	5	45	ю	2
	60	CHAR	1981/09/28	3:58:45	1.41	46.24	15.7	3.3	C	93	43	85	280	47	95	246	86	7	2	2
	61	EMC	1982/11/07	2:01:15	2.78	46.12	15.0	4.0	А	180	72	137	286	50	24	135	43	238	14	2
	62	EMC	1984/02/19	21:14:37	5.54	43.42	8.0	4.3	В	226	44	-153	336	72	-49	204	47	95	17	2
	63	CHAR	1985/02/11	7:06:01	1.64	46.32	14.1	3.4	C	75	70	б	344	87	160	298	16	31	12	2 *
	64	CHAR	1985/10/05	1:20:40	2.12	46.33	3.7	3.3	C	202	70	142	307	55	25	159	41	258	10	2
	65	CHAR	1986/02/19	13:27:00	1.39	46.28	14.5	3.9	В	295	68	5	203	85	158	157	19	251	12	2
	99	EMC	1986/02/25	17:10:39	4.72	43.95	5.0	3.6	C	203	43	-102	7	48	-79	212	82	105	с	2 *
	67	EMC	1987/02/05	9:59:37	4.56	43.66	5.0	3.5	C	356	72	-67	230	29	-140	236	57	104	24	2
	68	CHAR	1987/04/29	13:57:09	1.51	46.28	10.3	3.7	В	268	71	177	359	87	19	132	11	225	16	2
	69	EMC	1989/02/09	12:00:00	3.62	45.50	3.8	3.0	С	76	56	169	172	82	34	300	16	40	32	4
	70	EMC	1991/10/22	5:22:00	3.10	45.03	6.0	2.3	С	184	50	96	354	41	82	136	82	268	9	4 *
	71	EMC	1991/10/29	0.53:00	2.93	45.89	6.0	2.1	С	323	61	85	154	29	100	215	74	58	14	4
	72	EMC	1991/10/31	3:13:00	3.65	45.59	4.2	2.0	С	38	80	174	129	82	10	352	13	264	2	4
	73	EMC	1991/11/02	4:43:00	3.03	45.08	6.0	2.2	C	168	50	85	356	40	96	42	85	260	5	4
	74	EMC	1991/11/04	11:54:00	3.00	45.08	6.0	2.7	C	168	50	85	354	40	96	55	85	262	5	4
	75	EMC	1991/11/10	12:50:00	2.79	45.97	15.0	2.7	C	269	82	41	172	60	169	135	28	38	14	4
	76	EMC	1991/12/15	7:05:00	3.71	45.49	7.1	2.3	C	92	75	19	357	75	164	314	22	224	2	4
	LL	EMC	1992/01/13	17:44:00	3.46	45.09	3.6	2.5	C	5	70	171	98	82	20	322	20	232	5	4
	78	EMC	1992/02/04	7:37:00	3.03	45.08	4.1	2.4	С	346	44	84	174	48	96	148	85	259	Э	4
	79	EMC	1992/02/06	16:55:00	2.68	45.97	5.1	2.1	С	315	36	80	147	56	97	84	80	231	6	4 *
	80	EMC	1992/03/06	0:49:00	2.98	46.01	2.6	1.8	C	347	60	53	223	35	136	222	68	92	12	4
	81	EMC	1998/02/09	14:16:56	4.89	43.90	6.0	3.1	C	24	73	-78	239	21	-123	277	60	123	27	5

Geographical Number	Stress field	Date	Time (UTC)	Long.	Lat.	Depth	Mag	Quality		Plane	A		Plane	В	$P \not=$	txis	T A	xis	Ref. R.
area	zone	(DD/WW/DD)	(HH/MM/SS)	0	\odot	(km)	(IWI)		Az	Dip	Vect.	Az	Dip	Vect.	P az.	P dip.	T az. 7	dip.	
Charente region																			
82	CHAR	1972/09/07	22:26:56	-1.26	46.05	10.0	5.2	В	303	70	27	203	65	158	164	33	72	4	2
83	CHAR	1972/09/08	1:51:51	-1.45	45.95	10.0	4.1	в	303	70	27	203	65	158	164	33	72	4	2
84	CHAR	1975/12/28	2:16:07	0.594	46.45	12.0	3.9	C	190	87	162	281	74	ŝ	144	14	237	6	7
85	CHAR	1976/09/08	19:54:41	0.89	45.61	15.0	4.3	В	168	71	22	70	68	159	299	2	30	30	2
86	CHAR	1977/04/06	11:09:33	1.68	46.51	6.0	3.5	В	131	23	48	335	69	106	260	65	58	24	2
87	CHAR	1977/10/10	6:05:56	-1.43	45.96	5.0	4.7	В	305	60	8	211	83	150	164	26	262	16	7
88	CHAR	1978/05/27	7:47:40	-1.37	45.93	10.0	4.1	В	305	57	121	LL	4	51	269	63	13	7	7
89	CHMC	1983/04/21	1:53:08	0.99	46.18	5.0	4.0	А	122	85	31	29	60	174	252	17	350	25	2
90	CHAR	1983/05/08	17:47:51	-3.26	45.05	15.0	4.0	В	S	46	130	135	56	57	248	9	349	62	2
91	CHAR	1984/02/25	6:08:20	-1.75	46.02	10.0	4.2	В	300	70	50	188	4	151	166	49	58	15	2
92	CHAR	1984/04/08	7:20:21	-2.98	46.47	8.8	3.9	C	45	54	81	240	37	102	281	79	141	6	2
93	CHAR	1984/06/07	16:27:22	-3.09	46.30	10.0	3.8	C	302	64	121	68	40	43	10	13	257	59	2
94	CHAR	1985/10/07	13:01:49	-0.42	46.80	11.0	3.9	С	130	76	92	300	14	80	43	59	218	31	2
95	CHAR	1986/03/22	2:30:28	-3.83	46.50	20.0	4.1	В	272	86	27	180	70	176	138	17	4	12	2
Armorican Massif																			
96	NAM	1975/08/30	14:07:49	-3.11	48.85	3.0	4.5	В	265	85	135	360	45	7	213	33	320	25	2
67	SAM	1978/02/12	18:34:05	-1.67	47.73	2.0	4.1	В	92	42	LL	289	49	101	260	81	11	3	2
98	NAM	1978/09/20	15:40:40	-4.13	48.28	15.0	4.0	В	312	62	-124	LL	43	-44	18	11	271	58	2
66	NAM	1979/01/13	15:38:02	-3.28	48.36	7.0	3.9	C	95	80	53	352	38	164	330	43	213	26	2
100	NAM	1981/06/20	0:34:57	-3.82	49.06	8.7	3.7	С	75	79	137	175	48	15	26	37	131	19	2
101	CHMC	1981/08/31	6:14:29	-0.37	47.09	8.0	3.5	С	163	70	6	70	82	160	25	20	118	8	2
102	NAM	1981/09/04	4:42:01	-4.62	48.64	16.0	4.2	В	139	70	150	60	62	23	11	5	277	35	2
103	SAM	1982/11/09	13:44:46	-1.77	47.06	16.0	3.9	C	90	86	-166	181	76	4-	136	7	45	13	2
104	NAM	1983/07/07	3:52:24	-1.11	48.41	9.0	4.2	В	60	42	-73	262	50	-105	342	4	232	78	2
105	SAM	1983/08/14	15:35:51	-1.99	47.57	4.0	4.0	В	90	65	50	333	46	144	312	52	208	11	2
106	CHAR	1985/09/30	11:16:32	1.29	47.45	18.6	4.7	А	50	49	63	268	48	118	159	1	251	70	2 *
107	NAM	1987/01/10	0:51:15	-4.57	48.24	15.0	3.8	С	129	86	45	35	45	174	1	32	254	25	2
108	SAM	1987/01/15	14:21:15	-3.11	47.67	11.3	3.7	C	110	21	81	300	69	94	216	65	27	24	2
109	CHMC	1987/03/05	23:09:07	-0.15	47.12	7.0	3.3	С	100	40	-155	30	74	-53	261	48	147	20	2
110	NAM	1990/04/30	23:35:57	-2.1	49.10	10.8	3.5	C	35	75	90	215	15	06	305	60	125	30	Э
111	NAM	1990/11/08	18:21:47	-1.49	48.49	8.6	3.0	C	15	58	-70	230	37	-119	121	11	246	71	ю
112	NAM	1993/07/26	18:52:21	-1.11	48.77	7.8	3.5	C	115	45	-150	227	69	-49	346	14	93	49	Э
113	NAM	1994/09/17	6:05:03	-2.7	49.01	8.0	3.4	C	160	35	90	340	55	06	250	80	70	10	Э
114	NAM	1994/11/30	16:31:21	-0.57	49.44	14.0	4.1	В	105	25	50	328	71	107	262	60	45	24	З
115	NAM	1995/04/22	13:10:13	-2.35	48.62	9.5	3.5	С	95	75	70	330	25	142	340	56	201	27	З
116	NAM	1996/06/01	12:29:23	-1.32	49.35	7.5	3.0	С	125	70	180	35	90	0	348	14	82	14	З
117	NAM	1997/06/22	16:50:16	-2.27	49.20	13.1	3.4	C	285	80	158	19	68	11	240	21	333	7	Э
118	NAM	1998/08/08	10:36:16	-0.55	49.25	4.9	3.5	C	91	85	78	339	13	157	348	49	192	39	ŝ
119	NAM	1998/12/07	0:23:28	-1.65	48.58	9.6	3.3	С	150	55	100	313	36	76	94	LL	233	6	ŝ
References: (1) Santoire	(1976), (2) N	licolas et al. (1990). ((3) Amorese <i>et t</i>	1. (2000)	. (4) Do	rel et al.	(1995)	V. (5) Baron	tx et al.	(2001									
Revised focal mechanism	n solutions are	marked with a star.		L L						ļ	,								

Table 4 (Continued.)



Figure 7. Stress tensors computed for the five areas projected on a lower hemisphere Wulff diagram. Small arrows indicate slip vectors, large white arrows are extension and large black arrows are compression directions. Histograms are the number of focal mechanisms (N) versus the (τ, s) angular deviation, in degrees. Black triangle: σ_1 , diamond: σ_2 , square: σ_3 .



Figure 8. Stress tensors of the different areas. Black arrows indicate the direction of the maximum horizontal compression (σ_{Hmax}), white arrows indicate the direction of the minimum horizontal compression (σ_{Hmax}). Dotted areas circled in grey represent the regional extent of a particular stress field. NAM: North Armorican Massif, SAM: South Armorican Massif, CHMC: northeastern Charente and northwestern Massif Central, CHAR: western Massif Central and the Charente region, EMC: eastern Massif Central. SASZ: South Armorican shear zone, NASZ: North Armorican shear zone, QFZ: Quessoy fault zone, MFS: Mayenne fault system, SHF: Sillon Houiller fault.

6 INTERPRETATION OF THE RESULTS

6.1 Effect of the mantle plume

The EMC zone, is characterized by an extensional stress state, confirming the results of hydraulic tests in boreholes from Cornet & Burlet (1992), and the conclusions of Delouis et al. (1993) and Dorel et al. (1995), based on focal mechanisms analysis. Our study shows that the extension in the Massif Central is limited by the SHF in the west. Extension is probably related to the ascent of the hot mantle plume located beneath this area, that is inferred from teleseismic tomography (Granet et al. 1995a,b). The plume is believed to be the origin of an anomalous thermal regime of the crust related to volcanism (Vasseur 1982; Lucazeau et al. 1984; Lucazeau & Vasseur 1989). We propose that the extensional deviatoric stress is the result of bulging of the crust at the apex of the hot mantle plume. This implies that the SHF is acting as a passive boundary between the EMC and WMC. Thus, we infer a lithospherical scale to this fault. Inspection of digital elevation models (DEM) provides evidence that the eastern, volcanic, part of the Massif is uplifted with respect to the western part. On the basis of high-resolution DEM analysis, rivers and lava flows across faults, and the distribution and timing of sedimentation, Michon & Merle (2001) deduce a normal displacement along the SHF and associated faults that accommodate Quaternary uplift of the EMC.

Southeast of the Massif Central, Baroux *et al.* (2001) have shown that the Rhêne valley is actively in extension. These authors suggest that this extension is probably the result of the influence of the extensional stress regime of the Massif Central that they relate to the mantle plume. Focal mechanism inversions, in the present study, also show that the stress regime of the EMC and the Rhêne valley are consistent, confirming that extension in these two regions might have the same origin, namely the effect of the mantle plume.

6.2 Effect of plate and microplate tectonics

Alternatively, the observed stress perturbation could be related to intraplate forces. For instance, the anticlockwise rotation of Iberian microplate with regard to Eurasia and/or incipient subduction in the Bay of Biscay generates intraplate forces from which the deformation of the Pyrenees chain and the Bay of Biscay are the most clear expressions. In the west of our study area, the opening of the Bay of Biscay has accommodated the rotation of Iberia from its beginning at Aptian time, 114 Ma (Montardet *et al.* 1979; Olivet 1996). Nowadays, no large earthquakes are recorded offshore in the Bay of Biscay. Small earthquakes might occur but are not detected by French, Spanish and Portuguese networks. Accumulation of extensional stress on the SASZ or subparallel structures could be responsible for the $M_L > 5.0$ earthquakes that appear to be distributed all along

the Atlantic coast, following the fault zones (Fig. 6). NE–SW extensional stress in the SAM zone generates extension with a small dextral component on the northern part of the SASZ. As the southern branch of the SASZ is striking more N–S in the CHAR, the strike-slip component becomes more important. Forces associated with the rotation of Iberia generate, towards the North, compressional stress in the east and extensional stress in the west. In the east, the compressional stresses are accommodated by deformation of the Pyrenees. Thus, at the longitude of the northwestern Massif Central, the stress induced by the rotation of Iberia is null, because it is released in the eastern Pyrenees. Extension in CHMC ($\sigma_{\rm hmin}$ striking 132°NE) is parallel to the strike of the fan-shaped eastern termination of the SASZ, which strikes from ~120°NE to ~130°NE.

The coeval influence of Europe–Africa convergence and rotation of Iberia on pre-existing zones of weakness (mainly the SASZ), and the effect of the mantle plume beneath the Central Massif should partly explain the regional NW–SE compression and the short scale variations of the stress field computed by the inversion of focal mechanisms.

7 DISCUSSION

(i) Refinement of the image of the seismicity of western and central France, a slowly deforming intraplate region, has been accomplished by synthesis of seismological bulletins from different networks and the location of 4574 events. Earthquakes have then been relocated by joint hypocentres and velocity structure inversion. The new epicentre distribution points out that the seismicity of those regions is much less diffuse than it was previously thought. For instance, in the Massif Central, most events are aggregated in clusters. These clusters are concentrated in the most tectonically active parts of the Massif: along the north–south volcanic area, south of the Limagne graben and in the northwesternmost part of the Massif, where the SASZ is merging with the SHF. In western France, the epicentre distribution has been improved but it is still diffuse.

(ii) The computation of 44 new focal mechanisms and revision of some bibliographic solutions allow a better comprehension of the strain and stress distribution. The inversion of 119 focal mechanisms in central and western France illustrates the dependence of the resolution of the stress field on the amount and spatial distribution of the data. In 1993, over the same area, Delouis et al. only had 16 mechanisms available for analysis. Their result corresponds to an average stress field of the area (σ_1 close to the vertical, σ_2 horizontal and striking 125°NE, and σ_3 close to the horizontal and striking 35°NE), as the extensional focal mechanisms were not inverted separately. The local to regional size extensional zones defined by our study require a sufficient amount of data to be sampled. In theory, four mechanisms are enough to be inverted as we determine four parameters (σ_1 , σ_2 , σ_3 and R) during the inversion, but a minimum of six mechanisms is desirable. As opposed to hydraulic tests, the focal mechanisms do not provide direct measurements of the stress field. Several mechanisms must be inverted together, thus a computed stress field does not correspond to a single point but to data that encompass a larger region. The presence of local perturbations of the stress field can then introduce a bias in the inversion if all mechanisms are inverted together. Therefore, when direct measurements of the stress field are available in slowly deforming regions, a mismatch between the measured and computed stress field can indicate the presence of local perturbations of the stress field. Indeed, this study allows us to characterize two kinds of stress regimes, regional strike-slip versus local extensional.

(iii) The regional stress field in the study domain approximately agrees with the model configurations of Gölke & Coblentz (1996), relating it to the joint effect of the convergence of Africa and Europe and of the Mid-Atlantic ridge push. The extensional stress field corresponds to three perturbations of the regional stress field. We propose that they are the result of inherited lithospherical faults undergoing plate boundary and intraplate forces. Those plate boundary and intraplate forces originate from the convergence of Africa and Europe and the Mid-Atlantic ridge push, and by the rotation of the Iberian microplate, respectively. In the Massif Central, the SHF plays the role of a lithospheric scale barrier (i.e. passive boundary) between a western domain and an eastern domain uplifted by the thermal effect of a mantle plume at the base of the lithosphere

(iv) For the Provence area, Baroux et al. (2001) suggest that 'abrupt spatial stress changes in a narrow zone could reflect a tectonic model with upper crustal fragments (blocks) decoupled from the lithospheric mantle by the ductile lower crust as suggested by Müller et al. (1997) for short-scale variation of the tectonic regimes acting in western Europe'. In Provence, these authors observed stress field variations over a distance range of tens of kilometres. In our study area, the stress field variations have a minimum wavelength of more than 100 km, three times the crustal thickness. These variations are related to lithospheric rather than crustal scale processes, as proposed by Bonnet et al. (2000) for the development of relief in the Armorican Massif. Furthermore, the major structures influencing the stress field are of lithospheric scale (the SASZ and the SHF). Another argument to link these perturbations to lithospheric processes is the correlation between the geographic areas of stress perturbation and lateral variation of Pn anisotropy beneath France, as computed by Juhenderc & Granet (1999). The upper-mantle seismic anisotropy is believed to arise from preferred orientation of olivine grains, which are responding to the stress field during mantle deformation. Correlation between the true direction of anisotropy and crustal stress does not make it necessary to invoke decoupling of the crust in our study area. Nevertheless, east of the SHF, the extensional regime associated with high heat flow values $(>100 \text{ mW m}^{-2})$ could favour crustal decoupling. If crustal decoupling does occur, we believe that it is restricted in area to the extension of the thermal influence of the mantle plume: that is to say, the Massif Central east of the SHF, the Rhêne valley and the Provence region.

8 CONCLUSION

(i) Synthesis of seismological bulletins from different networks and the location of 4574 events, and precise relocation by joint hypocentres and velocity structure inversion allows improvement of the image of the seismicity of western and central France.

(ii) Taking into account the improvement in the hypocentral location of the events and in the velocity model, we computed realistic take-off angles. Then, we determined 44 new focal mechanism solutions and we revised the previously published focal mechanisms in order to construct a set of 119 homogeneously computed focal mechanisms.

(iii) The inversion of these focal mechanisms allows us to recognize a regional NW–SE compression. The regional strike-slip stress field appears to be overprinted by three local extensional perturbations. These are located in the EMC, in the SAM and at the southern termination of the SASZ, between the two massifs.

(iv) The stress field perturbations are of lithospherical scale and correlate with the lateral variation of Pn anisotropy, which is an

indirect consequence of stress orientation in the mantle. Thus, it is not necessary to invoke decoupling of the crust in our study area, as previous authors have suggested (Müller *et al.* 1997). If crustal decoupling does occur, we believe that it is restricted in area to the extension of the thermal influence of the mantle plume: that is to say, the Massif Central east of the SHF, the Rhêne Valley and the Provence region.

(v) Following Gölke & Coblentz (1996), we relate the regional strike-slip stress field to the joint effect of Europe–Africa convergence and Mid-Atlantic ridge push. We propose that the extensional deviatoric stress in the EMC is the result of the bulging of the crust at the apex of the hot mantle plume. The two other extensional areas approximately follow the SASZ. We argue in favour of intraplate extensional stress acting on pre-existing weak zones, and we relate those forces to the anticlockwise rotation of the Iberian microplate and/or incipient subduction in the Bay of Biscay.

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