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Precursors and fluid flows in the case of the 1996, $M_L = 5.2$ Saint-Paul-de-Fenouillet earthquake (Pyrenees, France): A complete pre-, co- and post-seismic scenario

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ABSTRACT

Earthquake precursors are now regularly described but often detected only after a major or moderate seismic event. Presence and influence of fluids in the seismogenic processes are often observed at the time of earthquake studies. Even today, the understanding of the physical processes involved in the source region is a real challenge for seismic hazard assessment. Here, the aftershock sequence of the $M_L = 5.2$, 1996 Saint-Paul-de-Fenouillet (Eastern Pyrenees, France) earthquake is first re-examined with *P*-wave cross-correlations, resulting in extracting three multiplets and in determining new locations. Multiplets and spatio-temporal distribution analysis of the aftershocks allow for quantifying the hydraulic diffusivity *D* at a maximum value of 5 m^2/s and the permeability *K* at 10^{-15} m^2 in the upper Pyrenean crust. Second, a model is established in order to explain the hydrogeochemical transient anomalies, which occurred during the 15 day-period preceding the 1996 earthquake. These anomalies consist on a temporal and spatial sequence of gas emissions in the epicentral area and on chloride and lead concentration variations in a bottled mineral water 25 km north to the main shock epicenter. The proposed model processed in a standard elastic half-space, consists of creep on a low-angle crustal normal-fault, generating volumetric strain field changes over a distance of 25 km from the epicentral area. This model is able to constrain not only the mechanisms and the locations of the geochemical anomalies, but also their timing and probable casual links to the triggering of the impending major event. Also, the active extension proposed here is compatible with seismological observations in the Pyrenees. Thus, the possibility of such creep, which can be considered as a slow-slip event, is discussed in the Pyrenean tectonic and geological context. The model is discussed and compared to previous proposed models on precursor processes of earthquakes, especially concerning the preparation zone concept. Finally, a complete seismic scenario over the period beginning 15 days before the quake and ending 5 days after is proposed and discussed.

1. Introduction

Detection of precursors and fluid flows before, during, and after earthquakes, and the understanding of the physical processes responsible for them, remain a challenge for geophysicists, especially related to the fundamental question of the predictability of earthquakes. Precursors may occur as transient geochemical and geophysical anomalies preceding earthquakes by a few months to a few hours. These precursors are of poorly understood origin (Ellsworth and Beroza, 1995; Dodge et al., 1996; Bernard, 2001; Wyss, 2001), necessitating accumulation of observations of different detectable signals in various seismotectonic contexts (Dodge et al., 1995; Bernard et al., 1997; Dal Moro and Zadro, 1999). Although precursors are principally observed for major earthquakes, they can also be detected for moderate earthquakes in continental domains (Bernard, 2001; Dodge et al., 1996; Dal Moro and Zadro, 1999; Skelton et al., 2008). The most frequently observed precursors are foreshocks occurring days or minutes before an earthquake, as they are "easier" to detect in densely instrumented regions (Dodge et al., 1995, 1996; Bernard et al., 1997). Other cases report crustal deformation in the impending epicentral area observed on tilt-meters, strain-meters, or water level variations in wells (Dal Moro and Zadro, 1999). In some cases, geochemical anomalies in spring water have been clearly identified and related to subsequent earthquakes, e.g. the 1995 $M = 7.2$ Kobe earthquake in Japan (Tsunogai and Wakita, 1995; Sugisaki et al., 1996) and two moderate $Mw \approx 5$ earthquakes in India (Skelton et al., 2008). In another example, which is part of this study, chloride and lead concentration anomalies were found in commercialized bottled groundwater preceding the 1996 $M_L = 5.2$ earthquake, which occurred at 7–8 km depth in the eastern part of the French Pyrenees, close to the city of Saint-Paul-de-Fenouillet (Toutain et al., 1997; Poitrasson et al., 1999). As described in this study, these anomalies were also preceded by gas emissions located in the epicentral area in the Agly River two weeks before the main shock (Rigo

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et al., 1997). Until now, no model has been proposed to explain the geophysical processes at the origin of these anomalies. On the other hand, the analysis of the aftershock sequence poorly constrains the fault plane and the focal mechanism of this event (Pauchet et al., 1999). In fact, the aftershock locations had a cluster pattern without any apparent alignments and the focal mechanisms reveal no internal coherency. This may suggest that the upper crust is highly fractured and most probably perturbed by the presence of fluids. In 2004, a micro-seismic sequence occurred in the epicentral area of the 1996 event, highlighting an unknown active crustal fault connected to the fault that ruptured in the 1996 main shock (Sylvander et al., 2007). The aim of this paper is to propose (1) a waveform analysis and a relocation of the 1996 aftershocks to characterize multiplets and the probable role of fluids during the post-seismic period, and (2) a possible and realistic model explaining the occurrence, locations and the chronology of the geophysical and hydrochemical observations. Although I am aware that other processes can explain the rare spatial and temporal sequence observed, I would like to test here a simple model to discuss some physical features of the concepts of preparation, nucleation, and relaxation of earthquakes in the continental domain.

2. Seismotectonic context

The Pyrenees are an EW trending belt about 400 km long resulting from the NS collision initiated 65 Ma ago of the Iberian and Eurasian plates (Choukroune, 1992). The major fault, called the North Pyrenean Fault (NPF), is considered as the surface trace of the suture between the two plates and seems to be inactive at the present time. From north to south, the mountain belt is divided into three geological units: the North Pyrenean Zone (NPZ) corresponding to the Eurasian margin, the Palaeozoic Axial Zone consisting of Hercynian material, and the South Pyrenean Zone overriding the Iberian plate to the south. According to GPS measurements, the present-day deformation rate across the range does not exceed 1 mm/yr (Nocquet and Calais, 2003). The seismic activity throughout the Pyrenean range is continuous and moderate ($M_w \leq 5$) (Souriau and Pauchet, 1998; Souriau et al., 2001), but historical events with destructive consequences, are known and well documented with maximum intensities estimated to be in the range VIII–IX (Lambert and Levret-Albaret, 1996).

On February 18th, 1996, a $M_L = 5.2$ earthquake occurred in the eastern Pyrenees, causing minor damage in the village of Saint-Paul-de-Fenouillet. The main shock occurring at 7.7 ± 1.2 km depth, and the following aftershocks were located in the granitic Agly Massif situated in the NPZ (Rigo et al., 1997; Pauchet et al., 1999). The geology of the studied region is illustrated in Fig. 1. The focal mechanism of the main shock is an EW-trending sinistral strike-slip fault with a small normal faulting component, and this event was been interpreted as the reactivation of a fault in the Agly Massif (Pauchet et al., 1999). Nevertheless, this interpretation suffers from a lack of knowledge of the crustal-scale geology of this area, especially from the unknown geometry of the Agly Massif at depth.

On May 2004, a micro-seismic sequence ($0.7 < M_L < 2.0$) occurred in the same area but located a few km to the north of the 1996 epicenter (Sylvander et al., 2007). Thanks to a precise location of these micro-seismic events and to a recent geological study of the Agly Massif (Olivier et al., 2004), an unknown low-angle active fault, dipping to the south below the NPZ, was evidenced, leading to a new interpretation of the 1996 event (Sylvander et al., 2007). Consequently, the 1996 earthquake is considered to have ruptured a fault plane located below the detachment at the base of the NPZ. This fault is connected at approximately 7 km depth to the fault delineated by the 2004 seismic swarm. Moreover, this interpretation is more consistent with the crustal structure deduced from refraction profiles (Gallart et al., 1980; Daignières et al., 1981) than the previous one. Thus, both the 1996 and 2004 seismic swarms are now considered as related to structures located in the basement, rather than related to the different tectonic discontinuities observed at surface in the NPZ, for which the evidence of present-day activity is not well established.

3. Relocated aftershock sequence

A temporary network of 18 short-period seismometers, operating from February 18 to February 23, recorded the aftershock sequence following the 1996 main event. The network was dismantled as a consequence of an abruptly decrease of the aftershock activity, even if the permanent network detected 115 aftershocks in the following 10-month period. These events because recorded by a sparse network have bad locations and then are not considered in the following. From the temporary network, a total of 336 aftershocks, among 415 reliable events, were located, using the Hypo71 code (Lee and Lahr, 1975), with hypocentral uncertainties of about 1.5 km. In addition, 39 fault-plane solutions were determined from first motions of *P*-waves (Pauchet et al., 1999). The aftershocks form a cluster over an area of 5 km × 7 km with an approximately WNW–ESE trend compatible with the EW nodal plane of the main shock focal mechanism (Rigo et al., 1997; Fig. 1). The cluster pattern and the variability of the aftershock fault plane solutions do not allow for a clear characterization of the geometry of the ruptured fault plane, making an unambiguous interpretation of this main event difficult.

In order to better understand the geological structures and the rupture processes implied in this unexpected Pyrenean earthquake, I re-analyze the aftershock sequence to search for possible occurrences of multiplets. Multiplets are a subset of earthquakes with very similar waveforms that occur close to each other. Among the 18 seismometers of the 1996 temporary network, 10 had digital recorders from which the waveforms are available. The multiplet selection and the time delay computations are performed using the cross-spectral method (Jenkins and Watts, 1968) improved with the coherency spectrum modulus (or coherency) of Got et al. (1994). The coherency is determined for each pair of events and characterizes the degree of similarity of the waveforms. In the following, I will refer to this processing as cross-correlation. Cross-correlations were applied to the 1916 *P*-waveforms from 415 reliable aftershocks. The maximum coherency obtained is 85%. Three classes of multiplets were identified and are referred as C1, C2 and C3 with 32, 23 and 18 events, respectively. Each class was then relocated with the HypoDD software (Waldhauser and Ellsworth, 2000), combining *P*- and *S*-wave arrival times and cross-correlation time delays. In order to have a homogeneous set of data, the 415 aftershocks were first relocated with HypoDD without the cross-correlation observations, multiplets corresponding to 17% of the events of the total data set. The 1-D *P*-wave velocity model used (Table 1) is the same as what used in previous studies in this area (Rigo et al., 1997; Pauchet et al., 1999; Sylvander et al., 2007). The *Vp*/*Vs* ratio used is 1.75 (Njike Kassala et al., 1992).

The final location of the aftershock sequence, obtained for 396 events, is presented on Fig. 1 with the events of the 2004 seismic swarm located by Sylvander et al. (2007). While the horizontal and vertical errors obtained by Pauchet et al. (1999) are approximately 1 km, the hypocentral uncertainty from HypoDD computations is estimated to be 0.3 km (Table 2). In contrast to the results shown by Pauchet et al. (1999), the aftershock cluster here is more concentrated (Fig. 1). Also, the pattern of the aftershock distribution in cross-section is more vertical than the previous study and seems limited to the north by the supposed ruptured fault.

Each class of multiplets was relocated separately with the same *P*-wave velocity model, taking into account the time delays computed by cross-correlation. From the results of HypoDD, 2 events in C1 had location instabilities and were removed. Finally, HypoDD successfully located 27 events, 20 events and 16 events for C1, C2 and C3 respectively, with computed hypocentral errors of less than 0.2 km