Tectonophysics 621 (2014) 123–131

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Seismicity in central-western Pyrenees (France): A consequence of the subsidence of dense exhumed bodies

Annie Souriau [a,*], Alexis Rigo [a], Matthieu Sylvander [a], Sébastien Benahmed [a], Frank Grimaud [b]

[a] IRAP/OMP, 14 Avenue Edouard Belin, 31400 Toulouse, France
[b] IRAP/OMP, 57 Avenue d'Azereix, 65000, Tarbes, France

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form 12 February 2014
Accepted 16 February 2014
Available online 22 February 2014

Keywords:
Pyrenees
Seismicity
Gravity
Tectonics
Stress field

ABSTRACT

The Pyrenees results from the convergence of the Iberian and Eurasian plates since Cenozoic, but the present stress regime of the range is debated, as most of the recent earthquakes exhibit normal solutions. We analyse the seismicity in central-western Pyrenees, which is the most active part of the range with the largest events. Seismicity maps obtained at different depths reveal quasi-periodic features in focus distribution, and a preferential occurrence of large earthquakes at the base of the upper crust. The superimposition of the seismicity to the gravity anomalies shows that earthquakes are mostly located on the southern border of positive Bouguer anomalies, which correspond to dense lower crust blocks trapped in the upper crust during the Pyrenean convergence. We propose that the seismicity results from the subsidence of these blocks previously exhumed inside pull-apart basins. This scenario explains all together the geographic distribution of the seismicity, its magnitude distribution and the predominance of normal focal solutions. It shows that the normal mechanisms do not necessarily imply a general north–south extension of the range, but may be compatible with a weak compressive regime, and that the stress field may not be uniform along the range.

1. Introduction

The geographic distribution of earthquakes inside intracontinental mountain belts is generally complex, and often poorly understood. It is however an important issue for seismogenesis, and for specifying the stress regime of the ranges. Several mechanisms like gravitational collapse, denudation, or lithospheric flexure, may contribute to the generation and activation of normal faults with different characteristics. For example, if gravitational collapse is invoked, the load due to the high elevation in the centre of the range results in a vertical stress that induces normal faults in the axial part of the range and thrust faults at the mountain foot (Molnar and Lyon-Caen, 1988). At the same time, the range is subject to horizontal spreading (Vernant et al., 2013). If denudation is the leading tectonic process, faults develop with similar characteristics, with normal faults in the high range and thrust faults on the borders (Avouac and Burov, 1996), but in opposition to gravitational collapse, no horizontal spreading of the range is observed (Vernant et al., 2013). Lithospheric flexure (Brunet, 1986) results from large sediment deposition and basin subsidence following a compressive episode and vigorous erosion; it may induce small events at the basin edge. Other factors like rheological contrasts (e.g. Chéry et al., 2001) and migration of fluids (e.g. Faulkner et al., 2010) also contribute to earthquake triggering on active faults.

* Corresponding author. Tel.: +33 5 61 33 29 64.
E-mail address: Annie.Souriau@irap.omp.eu (A. Souriau).

http://dx.doi.org/10.1016/j.tecto.2014.02.008
0040-1951/

In the Pyrenees, the recent studies of the largest earthquakes that occurred during the last decade show that almost all of them are at the foot of the relief and that they have normal focal mechanisms, contrary to what is expected from tectonic models invoking plate convergence. This observation raises the question of the mechanisms at the origin of the Pyrenean seismicity. The complex pattern of the seismicity suggests that there is probably not a single mechanism acting over the whole range (Lacan and Ortuño, 2012; Rigo et al., submitted for publication). In what follows, we will focus on the seismicity located in the vicinity of the western segment of the North Pyrenean Fault (NPF), a fault which delineates the boundary between Eurasian and Iberian plates. This segment corresponds to the most seismically active region of the range, and the activity is accurately known thanks to a dense permanent seismological network. Moreover, both the tectonic history and the structure are rather well documented. We will show that the seismicity is not governed by large tectonic features which involve the whole range equilibrium, but by local density heterogeneities of small size located in the crust. They may explain both the spatial distribution of earthquakes and the observed focal mechanisms.

2. The Pyrenean tectonic context

The Pyrenees is a narrow alpine range with roughly east–west orientation which stretches between Spain and France. The buildup of the range reactivated an eroded Hercynian orogeny, and involved two main phases (e.g., Choukroune, 1992):

1 A phase of extension (115–80 My) related to the opening of the Atlantic Ocean and of the Bay of Biscay. The Iberian plate underwent a senestral transcurrent motion followed by a counter clockwise rotation with respect to the Eurasian plate. This resulted in a rifting episode which opened a shallow sea at the present location of the range, with a thinned oceanic crust and the formation of compartmentalized pull-apart basins (Choukroune and Mattauer, 1978). The sea floor extension and the very thin crust favoured the exhumation of lower crust or upper mantle blocks through the upper crust in the western and central parts of the rift, thus blocks with density higher than the density of the surrounding crust (Jammes et al., 2010a).

2 A phase of convergence which started 65 Myr ago, and which is at the origin of the buildup of the range. It probably involved a subduction of Iberia beneath Eurasia. During this convergence episode, the blocks of dense material were likely squeezed upward and pinched in the sediments of the rift, following a mechanism proposed for the setup of the lherzolites (Vielzeuf and Kornprobst, 1984).

Many scenarios derived from plate reconstructions differ in the poles and angles of rotations, thus in the amount of shear and convergence (see Choukroune (1992) and Vissers and Meijer (2012) for discussion of some of the proposed models). The possibility of almost no transcurrent motion has been proposed. A large amount of subducted lithosphere with the presence of a detached slab has been invoked as being at the origin of the later extensional regime and mantle exhumation (Vissers and Meijer, 2012). The key point is that all the scenarios invoke distension and, for most of them, some amount of transcurrent motion between the two plates before convergence.

The structure of the range (Fig. 1) reflects this history (see Choukroune (1992) for a review). The Palaeozoic Axial Zone corresponds to the reactivated Hercynian structures; it includes large granitic massifs with the highest summits (up to 3400 m). It is limited to the north by the North Pyrenean Fault (NPF), which is generally considered as the northern boundary of the Iberian plate, even though the definition and precise tectonic role of this fault are subject to debate. The NPF strikes all along the range with an orientation about N100°E. North of the NPF, the North Pyrenean Zone corresponds to the Lower Cretaceous rift. It is a sedimentary folded unit which overrides the Aquitaine Basin along the North Pyrenean Frontal Thrust. To the south, the South Pyrenean Zone, made of Mesozoic and Cenozoic sediments, overthrusts the Molassic Ebro Basin.

The NPF may be defined by its lithospheric signature, as it corresponds to one of the most important Moho jumps in the world (Hirn et al., 1980). The Moho jump reaches 20 km in the central part of the range, where the crust is about 30 km thick beneath Aquitaine and up to 50 km thick beneath Iberia (Choukroune et al., 1990; Daignières et al., 1981; Gallart et al., 1981; Teixell, 1998). It remains large to the west but progressively decreases east of longitude 1.5°E to disappear close to the Mediterranean Sea. The thickness of the upper crust, which is the brittle part of the crust, is nearly the same (~12 km) on both sides of the NPF (Daignières et al., 1981; Gallart et al., 1981). On the other hand, a lithospheric thickening beneath Iberia seems to be required to explain the seismic wave travel times and amplitudes (Poupinet et al., 1992). From the gravimetric point of view, the very thick Iberian crust corresponds to an over-compensation of the range. The modelling of the Bouguer and geoid anomalies shows that the equilibrium of the range requires either a lithospheric root (Gunnell et al., 2008; Ledo et al., 2000), or a heavy, eclogitic crustal root (Vacher and Souriau, 2001), or a variation of the flexural rigidity of the crust along the range (Brunet, 1986).

3. The seismicity pattern

The seismicity of the range is determined thanks to about 40 seismic stations deployed over the whole range and operated by different organisations, mainly IGC (Institut Geológic de Catalunya) and IGN (Instituto Geográfico Nacional) in Spain and CEA (Commissariat à l'Energie Atomique) and OMP (Observatoire Midi-Pyrénées) in France. The mean distance between stations is about 35 km; it is only 25 km in the central-western French side, which is our region of interest. On the French side, the station locations have been very stable from 1997 to 2011; we will thus consider this time interval to ensure a coherency in the quality of our data. An estimation of the accuracy of the locations has been made by taking the opportunity of a seismic crisis near Lourdes, whose events could be located with a great accuracy thanks to temporary stations and to the availability of a 3D image of the local structure (Dubos et al., 2004). Assuming that these locations are true,

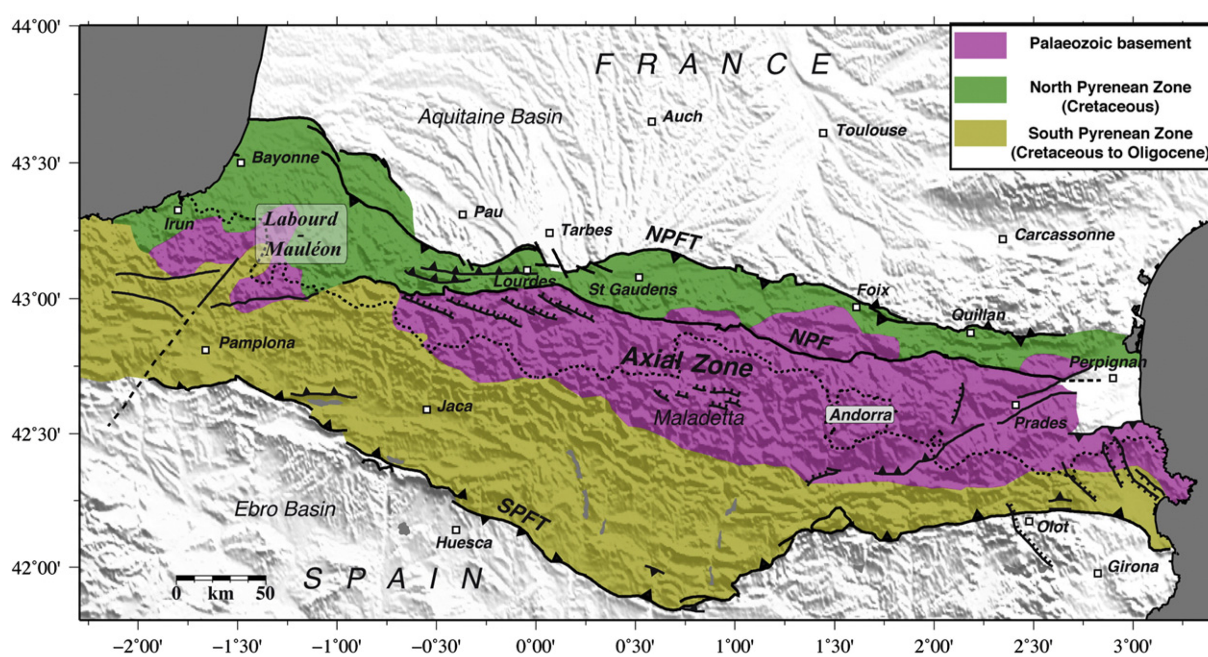

Fig. 1. Main structural units of the Pyrenees (redrawn after Choukroune, 1992). NPF: North Pyrenean Fault; NPFT: North Pyrenean Frontal Thrust; SPFT: South Pyrenean Frontal Thrust.