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An unknown active fault revealed by microseismicity in the south-east of France

Françoise Courboux, Christophe Larroque, Anne Deschamps, Céline Gélis, Julien Charreau, and Jean-François Stéphan

Géosciences Azur, CNRS, Nice-Sophia Antipolis University, France

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[1] A seismic swarm occurred in the south-east of France in December 2000, about 15 km north of the densely populated cities of the French-Riviera. More than 300 events were located by a dense temporary seismic network that had been installed in the epicentral region one month before. We evidence an alignment of the seismicity that we interpret as an unknown active fault. On the basis of regional tectonics, we propose that this fault results from basement faulting cutting through the detached overlying sedimentary cover. *INDEX TERMS*: 7230 Seismology: Seismicity and seismotectonics; 8123 Tectonophysics: Dynamics, seismotectonics; 8110 Tectonophysics: Continental tectonics—general (0905); 8107 Tectonophysics: Continental neotectonics; 9335 Information Related to Geographic Region: Europe. **Citation**: Courboux, F., C. Larroque, A. Deschamps, C. Gélis, J. Charreau, and J.-F. Stéphan, An unknown active fault revealed by microseismicity in the south-east of France, *Geophys. Res. Lett.*, 30(15), 1782, doi:10.1029/2003GL017171, 2003.

1. Introduction

[2] Even in regions of present-day low to moderate seismicity, large historical earthquakes have caused many damages [e.g., *Boschi et al.*, 1995; *Johnston*, 1996]. In such low deformation rate context, it is usually difficult to link the current and past seismic activity with active faults, which hinders our ability to understand active tectonics and assess seismic hazard. For instance, in the south-east of France, at the junction between the southern French Alps and the Ligurian Basin, several faults are supposed to be seismogenic (e.g., *Larroque et al.*, 2001) but without direct proofs: their geomorphological signatures are often hidden by erosion process, their slip rate is below the detection threshold of geodetic techniques, and the background seismic activity appears diffuse, without clearly delineating any linear structure. However, the representation of earthquake distribution is very likely biased by the lack of precise earthquake locations (error <3 km), impossible to achieve given the sparsity of permanent seismic stations and the heterogeneity of crustal structures.

[3] We therefore installed a dense array of seismic stations (one every 4–5 km) during a six month period in order to complement permanent networks near the densely populated French Riviera (SALAM campaign). In this paper, we describe and interpret a seismic crisis that, by

chance, occurred in the centre of our temporary network. We show how dense seismic station coverage helps to understand the links between microseismicity and active tectonics in this region.

2. Seismotectonic Context

[4] The studied area is located on the Mediterranean coast, at the termination of the Southern French Alps, between the high elevation crystalline massif of the Argentera and the low topographic Ligurian oceanic basin (Figure 1). The southern French Alps are part of the broad plate boundary zone between Eurasia and Africa. The two plates are converging at ~ 6 mm/yr in the western Mediterranean [*DeMets et al.*, 1994].

[5] Although this far-field kinematics framework seems well-constrained, the kinematics of the present-day deformation within the Africa-Eurasia plate boundary in the Western Mediterranean remains poorly known mainly because of the low strain rate and the complex tectonic structures inherited from the 100 My alpine history.

[6] The French Riviera is periodically affected by earthquakes of moderate magnitude. Two of them, in 1564 and 1887, are known to have caused the death of hundreds of people. Since 1920, at least 76 events in the 4–6 magnitude range or intensity larger than V (on the MCS scale) have occurred [*Larroque et al.*, 2001]. The seismological data (Figure 1) collected by permanent networks over the last 20 years show some alignments of epicentres along the Saorge-Taggia fault, [e.g., *Béthoux et al.*, 1998; *Eva et al.*, 2000] but, in general, the seismicity appears diffuse and does not delineate active faults.

[7] Regional and local geodetic studies [*Calais et al.*, 2000, 2002] show a north-south compression strain regime in the study area, with ~ 2 mm/yr of shortening across the southern French Alps. This strain regime is consistent with seismological (P-axes strikes of earthquakes) and micro-tectonic data that both evidence N-S to NW-SE compressional strain and stress in the Southern Alps during the Quaternary [*Baroux et al.*, 2000].

[8] The area of the temporary SALAM seismological experiment is the so-called “arc de Nice” (Figure 1). It is composed by south-verging fold and thrusts involving series of Mesozoic to Paleogene ~ 1300 meters-thick sediments. This fold and thrust belt was translated southward, above a décollement zone lying at the base of the sedimentary cover in Triassic evaporites, during the last alpine compressional phase, around 10 My ago [*Bullard et al.*, 1975; *Perez*, 1975]. Below the sedimentary cover, the crystalline basement has undergone deformation since the Paleozoic, with

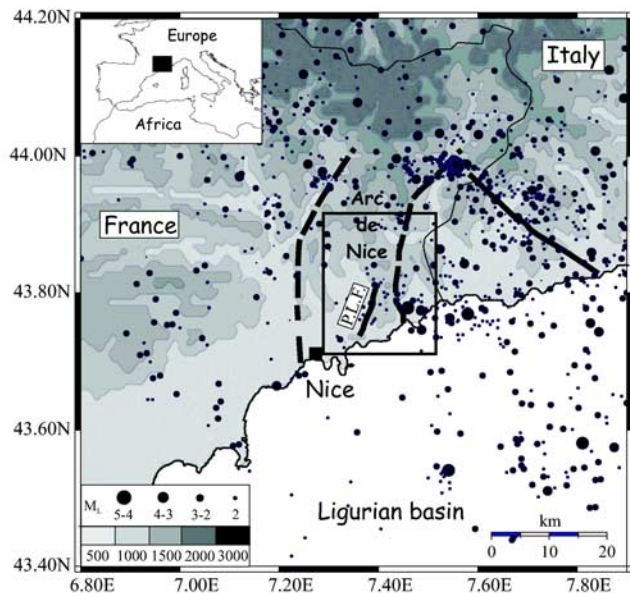


Figure 1. Topographic map of the Southern Alps – Ligurian basin area (data are from IGN). The seismicity for the last twenty years is from the ReNaSS French network. The supposed active faults are in bold (from Larroque et al., 2001), PLF and STF is the Saorge-Taggia fault. The studied area (square) is the southern part of the so-called “arc de Nice”.

major hercynian basement structures striking E-W and NNE-SSW.

3. A Seismic Crisis in the Center of the Temporary Network

[9] We installed from October 2000 to April 2001 a very dense seismic network (one station every 4–5 km) in order to accurately locate the micro-seismicity over a 20 by 20 km

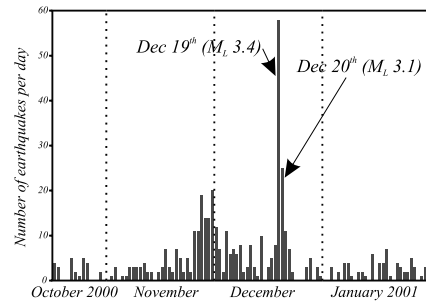


Figure 2. Temporal distribution of seismicity recorded by the temporary network.

area. We chose to place this network in a small region very close to the Mediterranean coast and populated cities of Nice, Monaco, and Menton (Figure 1), around the location of a $M_l = 3.4$ earthquake that had occurred in 1999 and had been felt in Nice [Courboulex et al., 2001]. The seismic network consisted of 20 3-components stations equipped with short period or broad-band sensors, all connected to GPS antenna for timing. These stations operated in continuous mode with a sampling frequency of 125 Hz during 6 months. They allowed for the detection and location of about 640 events both on land and offshore, whereas the permanent networks detected only 77 events.

[10] This paper focuses on the study of the 370 events of a seismic crisis (called the Blausasc crisis) that luckily occurred inside the temporary network, in the epicentral area of the 1999 Peille earthquake. This crisis began a few weeks after the installation of the seismic stations with an increase of the number of earthquakes per day starting at the end of November. The activity was maximal on December 19th, with more than 60 events detected in one day (Figure 2). The earthquakes were felt in the villages around the epicentres. As during the 1999 Peille earthquake, the two largest events, although of small magnitude (M_l 3.4 and

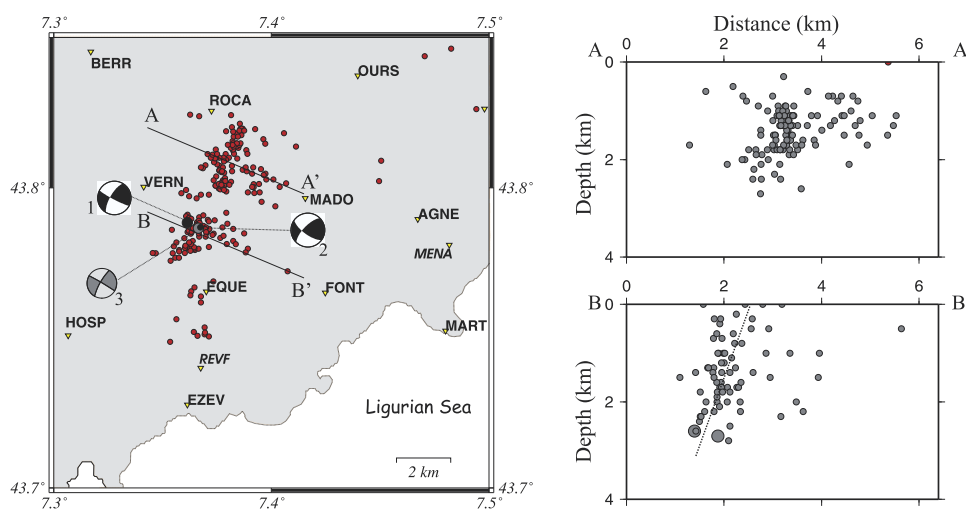


Figure 3. Epicentral distribution (left) of the Blausasc crisis events located by the temporary network. Earthquakes within ± 2 km from the profile AA' and ± 1 km from the profile BB' are plotted in the sections where depth origin is the sea level (right). All stations (triangle) belong to the temporary network except REVF and MENA ReNaSS and RAP French networks. The focal mechanisms and locations are plotted for the 2000 Dec. 19th event (1), the 2000 Dec. 20th event (2) and the 1999 Peille event (3, relative location). On the profile B-B', the two main shocks of the crisis correspond to the large circles.

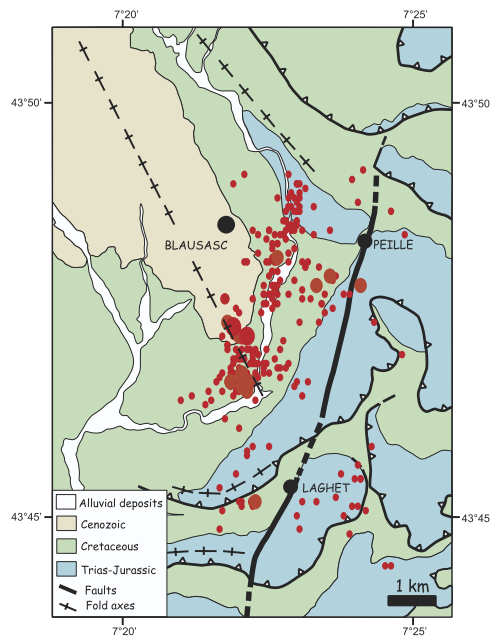


Figure 4. Simplified geological map of the Blausasc area [modified from Gèze *et al.*, 1968]. The epicentre alignment is located 2.5 km west of the Peille-Laghet fault above the Paillon valley.

Ml 3.1), were also felt by most of the inhabitants of the densely populated cities along the coast.

[11] We first picked P and S waves on each of the 370 events of the crisis and located them using the HYPOCENTER code and SEISAN software [Haskov and Ottemöller, 1999]. We tested several velocity models using the tomographic code VELEST [Kissling *et al.*, 1994] and a grid search approach as an input. We finally converged towards a simple layered model with a constant velocity increase with depth. We also searched for the best V_P/V_S ratio and found a value of 1.73. We obtained a low average rms, from 0.09 sec (for all the events) to 0.12 sec (for the events recorded on 8 stations and more). For these events, the mean error in location is 1.2 km on the horizontal direction and 1.4 km on depth.

[12] We find that the epicentre distribution follows a N20E trending linear alignment with two seismicity clusters separated by a small gap. In the southern cluster, the depth distribution, taken into account the mean location

errors, is compatible with a structure dipping west about 70° from 3.5 km depth to the surface (Figure 3). The basement depth in this area is not precisely known but estimated to be at 1.3 ± 0.3 km below the surface from the mean thickness of the overlying sedimentary layer. This implies that the Blausasc crisis affects both the basement and its sedimentary cover, with a clearer activation of the more surficial layers in the southern swarm. We also observed a migration of the seismic activity from north (November) to south (December).

[13] The focal mechanisms of the two larger shocks computed using about 20 P-wave polarities on each event reveal a strike-slip movement. For both events, one of the two nodal planes is in good agreement with the N20E alignment of the seismicity, favoring a left-lateral movement along this fault (Figure 3). These focal solutions are very well constrained.

4. Image of an Unknown Fault

[14] The structure imaged by our dense seismic network during the Blausasc crisis is likely to be an active fault. During the crisis, the faulting extends from 3 km depth up to 0.5 km depth. At surface, it corresponds in the morphology to the Paillon valley, where no fault is currently mapped. The closest fault, the Peille-Laghet fault, is located about 2.5 km to the east of the Blausasc seismic swarm and trends roughly parallel to the seismic alignment found here (Figure 4). We verified that this shift was not due to a systematic error in the location process due to lateral heterogeneities in the velocity model. We measured the polarization direction of the P waves at the closest stations for several events. The azimuth systematically pointed towards the epicentre obtained by the location procedure. We then excluded the hypothesis of a systematic shift error in the location process.

[15] The Peille-Laghet fault is at least 10 km long, it cross-cuts the sedimentary cover in a N20E strike, and dips 70° W. Its geological evolution is complex: from normal faulting during a Cretaceous extensional phase to left-lateral strike-slip faulting during the Miocene compressional phase that had involved the emplacement of the “arc de Nice” imbricate stack [Malavieille and Ritz, 1989; Ritz, 1992]. In the morphology, the Peille-Laghet fault crosscuts crests and valleys. However, field and aerial photograph investigations show no evidence of morphotectonic anomalies that could suggest a recent activity of that fault.

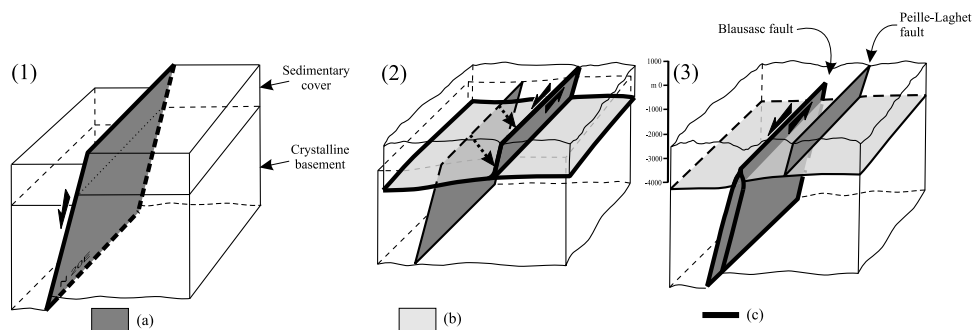


Figure 5. Cretaceous to present-day 3D-tectonic evolution of the Blausasc fault: (1) Cretaceous extensional faulting, (2) Miocene thin skin deformations: coupling between N170E thrusting above the basal décollement and left-lateral faulting in the sedimentary cover and (3) Present-day strike-slip reactivation of the deep part of the fault.

[16] The 1999 Peille earthquake occurred close to the Peille-Laghet fault with a focal mechanism consistent with left-lateral strike-slip on a steep N30E plane (Figure 3). However, this event was located using the permanent seismological network, which was insufficient to associate it without ambiguity with the surface trace of the Peille-Laghet fault [Courboulex *et al.*, 2001].

[17] In order to test the relationship between the 1999 Peille event and the 2000 Blausasc swarm, we performed a relative location process. We chose the largest and best located event of the Blausasc swarm, the Dec 19th, $M_l = 3.4$ event, that had been well recorded by both permanent and temporary networks, and relocate the Peille event relatively using a standard master event technique. We find that the 1999 earthquake occurred almost at the same place than the two larger shocks of the Blausasc crisis. This proximity of the three events is also attested by their waveform similarity. Therefore, the seismic activity recorded during the SALAM experiment as well as the 1999 Peille event occurred on an unknown deep-seated active fault with no clear morphological expression. Let us call this hidden structure the Blausasc fault.

[18] What is the origin of this fault that affects the basement? This fault is part of the “arc de Nice”, that was decoupled from the crystalline basement during the Miocene (15–5 Ma), with folding and SSE thrusting of the sedimentary cover [Malavieille and Ritz, 1989]. From field work and balanced geological cross sections (unfolding of the strata is based on the restoration of the lower Jurassic competent layer), we restored the position of the Peille-Laghet fault trace before the Miocene compressional events. We find a 4–5 km displacement in a N170E direction, which places the paleo-position of the Peille-Laghet fault approximately on top of the Blausasc fault (Figure 4). This displacement, corresponding to 27% of shortening in the sedimentary cover, is consistent with the shortening depicted in the western part of the belt [Laurent *et al.*, 2000].

[19] We therefore propose an hypothesis to explain the present-day seismicity pattern and the regional tectonic evolution (Figure 5): (1) the Peille-Laghet normal fault developed during Cretaceous times; (2) in Miocene times, the compressional thin-skin tectonics led to the southward thrusting of the sedimentary cover. During this period, the inherited Peille-Laghet fault had been reactivated: the upper part of the fault, affecting the sedimentary cover, was decapitated from its root in the basement and reactivated by left-lateral faulting, whereas its basement part remained mainly inactive.

[20] In our interpretation, the Peille-Laghet fault has been inactive since the end of the Miocene thrusting. At present, faulting in the basement propagates in the sedimentary cover, delineating the Blausasc fault, but without reaching the surface. For instance, the NW-SE folds near Blausasc are not shifted and no scarp trace of faulting has been evidenced in the Paillon valley (Figure 4).

5. Conclusion

[21] We have used a new accurate seismological data set collected during a dense temporary experiment, to image an unknown active fault (Blausasc fault) in the backcountry of

Nice. We propose that this fault corresponds to the basement structure of an inherited normal fault generated in the Cretaceous times and hidden by later compressional phase. Our results show that a dense seismological network is essential to detect and accurately locate microseismicity and then, image active structures in regions of moderate to low seismicity. It also highlights the fact that surface traces of fault have to be used with suspicion in regions with complex inherited tectonics. The Blausasc fault, because of its proximity of highly populated zones along the Mediterranean coast has to be now taken into account in seismic hazard estimation.

[22] **Acknowledgments.** We thank the participants to the SALAM campaign from Géosciences Azur, A-M Duval, Jean-Louis Perez and Sylvain Vidal from CETE Méditerranée and Philippe Mondielli from Division des Risques Naturels de Monaco. A special thank to Eric Calais who carefully commented the manuscript and to Massimiliano Barchi for fruitful discussion and very precise review of the paper. This work has been funded by PNRN, ACI Catnat and RAP French projects. Publication n° 568 of Géosciences Azur.

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