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200-m-deep earthquake swarm in Tricastin (lower Rhône Valley, France) accounts for noisy seismicity over past centuries

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ABSTRACT

In the lower Rhône Valley (France), the Tricastin area was struck in 2002–2003 by an earthquake swarm with a maximum M_L-magnitude of 1.7. These shocks would have gone unnoticed if they had not occurred beneath habitations and close to the surface, some events being only 200-m deep. A several months' monitoring of the seismic activity by a 16-station mobile network showed that earthquakes clustered along a N–S-trending, at least 5-km long, shallow rupture zone, with no corresponding fault mapped in the surface. Half of the seismic events occurred in a massive, *c.* 250-m-thick, Lower Cretaceous limestone slab that outcrops near by. Since the late eighteenth century, several much more severe earthquake swarms have struck Tricastin. The 1772–1773 and 1933–1936 swarms were prolific and protracted, with reports of numerous detonations and even damage. Obviously, the abnormal noises that caused panic in the past centuries can be explained by the shallowness of the phenomena, a 200-m focal depth being perhaps a record value for tectonic earthquakes.

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Introduction

Between the French Massif Central to the west and the Alps to the east, the 'Sillon Rhôdanien' (Fig. 1) is the southern branch of the European Cainozoic Rift System that dislocated western Europe from the North Sea to the Mediterranean (Dèzes *et al.*, 2004). In its middle part, midway between Valence and Avignon, the Tricastin area has long been recognized as the seat of long-lasting earthquake swarms: besides the classical way of releasing seismic energy through mainshock–aftershock sequences, earthquake swarms are characterized by long series of large and small shocks, with no outstanding principal event. The term 'Schwarmbeben' (i.e. 'swarm quake') was first used by Knett (1899) to describe the random seismic activity observed in the border region between Germany and the Czech Republic (Vogtland/NW Bohemia), where this phenomenon is frequent.

Swarms are common in volcanic regions such as Japan, Central Italy, Afar or oceanic ridges where they occur before and during eruptions. They are also observed in zones of Quaternary volcanism such as Vogtland/NW Bohemia, where fluid migration in a magmatic environment can be invoked (e.g. Hainzl and Fischer, 2002). In intraplate regions (Špičák, 2000) or orogenic belts, for instance in the western Alps (Jenatton *et al.*, 2007), the dynamic evolution of earthquake swarms remains more mysterious, even if fluid migration is a likely regulating factor (Daniel *et al.*, 2009).

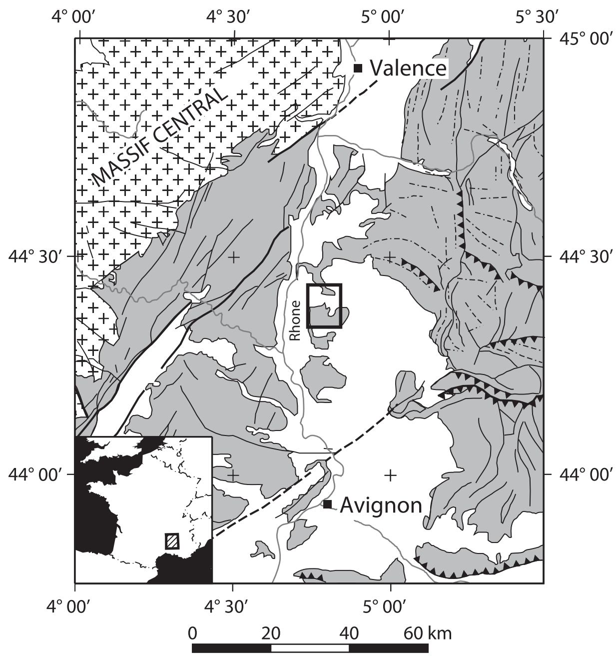

Fig. 1 Simplified map of the southern Rhône Valley, with main geological contours after Service de la Carte géologique de la France (1969): cross pattern, French Massif Central; shaded, Mesozoic; blank, Cainozoic and Quaternary; barbed lines, main thrusts; other faults mainly involve strike-slip motion. Dash-dotted lines in the eastern part of the map: fold axes from Gratier *et al.* (1989). Box: study area of Fig. 2.

Although hydrothermal sources are documented, Tricastin is clearly not a volcanic region. The boundary between Eurasia and the colliding Adriatic microplate, usually likened to the

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Piedmont seismic arc in Italy, is located 200 km to the east (Thouvenot and Fréchet, 2006). The Provençal domain of the Alpine belt begins just to the east of Tricastin, but the most active part of the orogen in terms of deformation and seismicity is located 150 km farther east. Thus, although Tricastin is sited in the Sillon Rhôdanien, which indeed has suffered extension since the Cainozoic, one may rather classify it as an intraplate region.

Two of the earthquake swarms that struck Tricastin in 1772–1773 and 1933–1936 have been described in testimonies as accompanied by explosion noises similar to cannonades. Rothé (1936) first evoked shallow seismicity to explain these auditory phenomena, but he lacked reliable seismic data to argue this point, and anyway shallow focal depths were considered with scepticism at that time when earthquakes were believed to be usually seated much deeper in the crust.

What seismologists now consider as 'shallow seismicity' is of course a matter of scale. At a global scale, 'shallow' earthquakes are those that occur in the first 40 km of the Earth's interior. Man-made or volcanic seismicity documents events much closer to the surface. In mines or gas fields, seismicity usually occurs between the surface and the depleted layers, and focal depth values of a few hundred metres are common. Earthquakes owing to dam filling usually occur much deeper in the crust beneath the reservoir. Dry-rock experiments show that fracturing occurs in a several hundred-metre zone over and below the injection point, which is usually several-kilometre deep (e.g. Phillips, 2000). However, a thorough search in the literature for shallow tectonic earthquakes does not provide any evidence for foci shallower than 1 or 2 km. In the following, the term 'ultra-shallow seismicity' will be used to refer to events with focal depths shallower than 1 km.

The Tricastin 2002–2003 earthquake swarm revived memories of the conflagration-like noises heard in the previous episodes. When we became aware of this phenomenon, we judged that it offered a rare opportunity to understand its origin, all the more so as it could evolve into a sequence of destructive events, in the close vicinity (10 km) to major nuclear installations on the western bank of the Rhône river. This article details information gained by the deployment of a temporary seismic network, and insists on the fact that observed events were indeed ultra-shallow.

Stratigraphy and tectonics

Our study area is 44°20.5′N–44°26′N and 4°44′E–4°50.5′E (Box, Fig. 1). Between the widely stretched-out Rhône Valley to the west and the Visan Miocene Basin to the east, Tricastin emerges as a region of Cretaceous and Cainozoic jagged hills, with outcropping stratigraphy ranging from Barremian (118–106 Ma) to Burdigalian (20–15 Ma). The Upper Barremian stage is characterized, as elsewhere in southeast France, by the Urgonian facies. This massive, hard, white, reef limestone formation has an approximate thickness of 250 m (Service de la Carte géologique de la France, 1975). In the study area, it outcrops only in a limited flat zone, to the southeast of La Garde-Adhémar (Fig. 2). Seismic and electric exploration in the whole Tricastin area indicates that the top of the Urgonian slab, often only a few tens of metres deep, is slashed by a complex fault network (Service de la Carte géologique de la France, 1964).

Major faults, west of the Rhône River, involve mostly strike slip along the N40–N60°E Hercynian direction (Fig. 1). Some probably extend farther to the east, where they meet the Alpine domain, here characterized by north- and south-verging thrusts, and N–S-striking faults. Most probably because of their poor preservation within loose sedimentation, few tectonic fractures are known in the study area. However, seismic exploration recognized several Upper Miocene N–S-striking normal faults in the Rhône Valley. With throws reaching several hundred metres, their juxtapo-

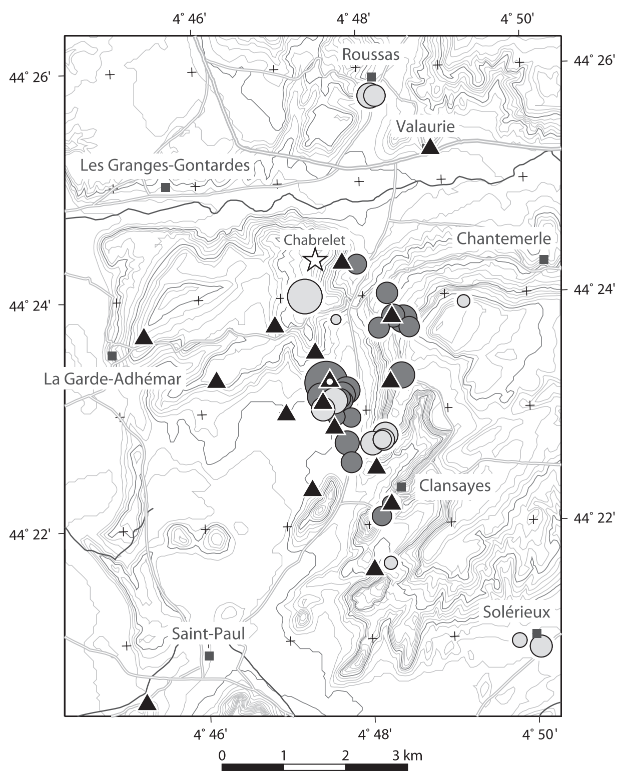

Fig. 2 Temporary seismological stations (triangles) and 38 HYPODD relocated earthquakes, with a lighter shade for events shallower than 200 m. Symbol size is proportional to the magnitude. Station CLAN marked by a white dot; Chabrelet is the hypothetical epicentre of the 1936 earthquake swarm. Topographical contours are at 10-m vertical intervals.

sition makes this zone a real rift (Service de la Carte géologique de la France, 1964). In the study area, other minor features affect Aquitanian limestones to the northeast of La Garde-Adhémar, where several conjugate faults striking NW–SE and SW–NE are documented.

Historical seismicity

The earthquake swarm that visited Tricastin between June 1772 and December 1773 is particularly well documented by a contemporaneous four-page report (Revol, 1773) and a geological investigation (Faujas de Saint-Fond, 1781). It affected the whole study area shown in Fig. 2 (Clansayes, Solérieux, Chantemerle, Valaurie, Les Granges-Gontardes), with more than 60 felt events (Boisse, 1936; Rothé, 1941). The old village of Clansayes, perched on an outlier, had its church tower knocked down by the strongest event of the sequence (23 January 1773, maximum MSK intensity I_{max} = VII–VIII). According to Revol (1773), the epicentral area seems to have migrated afterwards, and houses at Saint-Raphaël (Solérieux), to the southeast of Clansayes, suffered cracking damage from subsequent events. Faujas de Saint-Fond (1781) conversely states that, at the end of the swarm in 1773, earthquakes were more felt in villages to the northwest of Clansayes. Throughout the 19 months of the swarm, underground noises similar to cannon explosions were reported, whereas earth vibrations did not seem to be systematically noticeable.

In 1933–1936, another swarm visited the same area. This time most of the underground noises were reported in the northern villages of Les Granges-Gontardes and La Garde-Adhémar (Rothé, 1936) – although this statement might be biased by the detailed observations left by Abbé Boisse who precisely exercised his priesthood at Les Granges-Gontardes. The swarm was active between October 1933 and December 1934. After 10 months of quiescence, the activity burst again in October 1935 till August 1936. The total swarm activity amounted to 24 months, with a climax being reached by mid-May 1934 when shocks were reported to be felt every minute during the night of the 11–12 May 1934 (Boisse, 1936). A few hours later, a stronger shock damaged several churches and houses at Vallaurie, Roussas and La Garde-Adhémar, with chimneys and one church tower knocked down (12 May 1934, I_{max} = VII). Further slight damage was reported at Clansayes on 11 January 1936 (I_{max} = V), and at La Garde-Adhémar and Les Granges-Gontardes on 13 February 1936 (I_{max} = VI; Rothé, 1939a).

From the report of underground noises, Rothé (1936) estimated that the epicentre was situated at Chabrelet, southeast of Les Granges-Gontardes (Fig. 2). He first tried to determine the focal depth of an event that occurred during the night of the 11–12 May 1934, and which was particularly well recorded by four seismological observatories (Clermont and Strasbourg in France; Neuchâtel and Zurich in Switzerland). The closest instrument (Clermont) being 200 km away, this attempt was doomed to failure. However, Rothé believed a 0-km focal depth better fitted observed arrival times. He also tried (Rothé, 1939b) to use isoseismal curves observed for the 13 February 1936 event, but the various empiric relations he used provided scattered values (between 4 and 18 km). He judged them unrealistic. In one last attempt, Rothé (1939b) made use of records provided for the 1936 active period by two horizontal Mainka-SOM seismographs, which had been installed at Les Granges-Gontardes in July 1934. From the average S–P interval of 1.2 s, and taking into account that the station was 2.5 km away from his preferred epicentral zone, he computed a focal depth of 3 km. However, when we scrutinized original seismograms recorded on smoked paper with a drum speed of 0.25 mm s^{-1}, we found such minute S–P intervals hardly discernable. From all these attempts, one concludes that the shocks were shallow, even if one cannot prove that they were ultra-shallow.

The 2002–2003 earthquake swarm

The 2002–2003 earthquake swarm initiated at the beginning of December 2002 by shocks perceived as explosions by the inhabitants of a *c.* 20-house hamlet close to Clansayes. These abnormal sounds were not at once identified as earthquakes by the inhabitants because local earthquakes are inexistent in the inter-swarm quiescence periods, and – to our knowledge – the latest felt swarm dates back to 1933–1936. A temporary velocimetric station (CLAN) was installed in the basement of one of the houses at the end of December 2002.

On several seismograms recorded by this station, we observed events with an S–P interval of only 45 ms (Fig. 3), which implies a very shallow focus. In the first minutes of the New Year's Day, 2003 (31 December 2002 UTC), two stronger (and felt) earthquakes occurred at 23:19 (M_L = 1.3) and 23:20 (M_L = 1.7), both with S–P intervals of about 100 ms. It prompted us to install another 15 mobile stations (Fig. 2): 11 were fitted with velocimeters and 4 with accelerometers from the French mobile accelerometric network. Although this network has been operated for 8 months, seismic events were detected only during the first three months. During this period (10 January–7 April 2003), we located 51 events with magnitudes ranging from

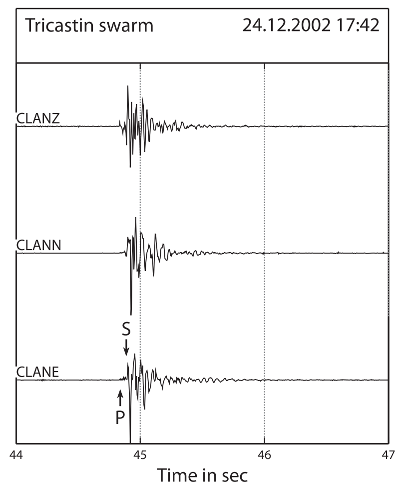

Fig. 3 Tricastin swarm earthquake recorded by three-component station CLAN in the epicentral area (see position in Fig. 2). Seismometers have a 2-Hz natural frequency. Amplitude window for each component (vertical, N–S and E–W) is ± 100 μm s^{-1}. Three-second time scale; sampling frequency is 200 Hz. The minute 45-ms S–P interval is clearer on the E–W component, bottom signal.

−0.7 to 1.4. For the present study, earthquakes were first picked and located using the PICKEV2000 software (Fréchet and Thouvenot, 2000), which enables an interactive control of picks. We then used HYPREF2005 (Fréchet, 2005), a modified version of the HYPO71 programme (Lee and Lahr, 1975), with a one-dimensional velocity model consisting of two 100-m thick layers, with P-wave velocities of 2 and 4 km s^{-1}, and a 5.3 km s^{-1} medium underneath (S-wave velocities were derived by assuming a V_P/V_S ratio of 1.71). This model was built on velocity measurements obtained for similar sedimentary series at the Eguilles borehole, to the south of Avignon (Mari, 1977). We eventually formed travel time differences from P- and S-picks and used the HYPODD programme (Waldhauser and Ellsworth, 2000; Waldhauser, 2001) to improve location precision.

Out of the initial 51 events, 38 only were relocated (Fig. 2) because relocation demands a higher data quality, and events recorded by too few stations are excluded. We prefer relocated events which, although fewer, are more reliable (Jenatton *et al.*, 2007). Although relocation involves relative positioning, we have a good control here on how the centroid of the relocated swarm is positioned: the largest-magnitude event (1.4) that occurred on 26 January 2003 (Fig. 4) is relocated right beneath the station CLAN (triangle with white dot in Fig. 2), in accordance with what could be ascertained from a P-wave almost exclusively recorded on the vertical component at that station. However, we note a slight vertical discrepancy between the 400-m relocated depth (relative to sea level), and the 45-ms S–P interval observed at that station, which rather corresponds to a 200-m focal depth (relative to the sea level, with a mean surface elevation of 100 m). We have not attempted to correct this, which means that depth values used in the following might be overestimated (but by 200 m at most).

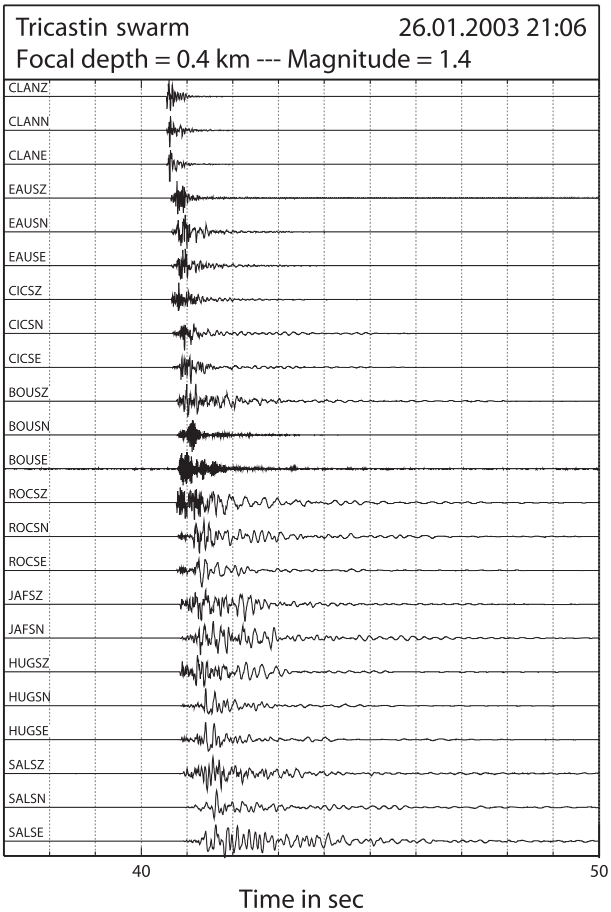

Fig. 4 Example of normalized amplitude signals recorded by stations of the temporary network for the M_L-1.4 26 January 2003 earthquake. Thirteen-second time scale; epicentral distances range from 0.2 km (top) to 2 km (bottom). Amplitude windows range from ± 300 μm s^{-1} (top) to ± 9 μm s^{-1} (bottom).

Although activity was maximal right beneath CLAN (Fig. 2), other shocks were detected along a N–S-trending zone whose length reaches at least 5 km, even if one excludes the few events that occurred at Roussas and Solérieux. Half of the events occurred in the 0–200-m depth range (Fig. 5); half of the remaining foci clustered in the 400–600-m depth range; few others occurred at a depth of about 1000 m. Migration of epicentres with time is uneasy to detect. However, earlier events in the series were deeper and more clustered in the central part of the active zone (Fig. 6). While becoming shallower, activity has migrated southwards and northwards since the beginning of February.

Figure 7 shows the complete time series for the earthquake swarm. Station CLAN, installed in December 2002, recorded many small-magnitude shocks whose epicentres cannot be located. For most of them, P- and S-wave arrivals can be read on seismograms. We considered that an event belonged to the earthquake swarm whenever the observed S–P interval was smaller than 500 ms. These earthquakes daily recorded at CLAN provide an estimate of the swarm activity. For 79 events that could not be located, we estimated the M_L magnitude by assuming that earthquakes were beneath CLAN. Figure 7 also includes magnitudes for the 51 earthquakes located by the temporary network, so that the magnitude series totals 130 events, with magnitude ranging from −1.3 to 1.7. Activity was variable in the course of the 4 months' period. The two New Year's Day shocks indisputably generated aftershocks, whereas other 'large' shocks in January and March did not. For located events, we observed variable intervals between consecutive events, ranging from less than 1.5 s to more than 10 days.

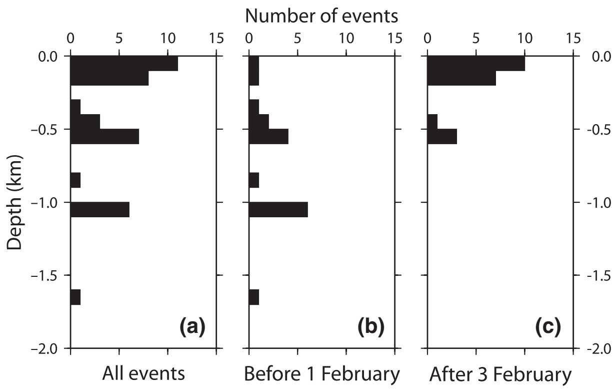

Fig. 5 Depth histograms for the 38 relocated earthquakes. (a) All events; (b) events before 1 February 2003; (c) events after 2 February 2003.

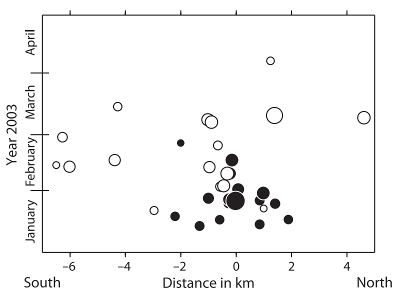

Fig. 6 As a function of time (vertical axis), position of epicentres along the N–S axis (km 0 is station CLAN, dotted triangle in Fig. 2). Each event is represented by a circle with radius proportional to the magnitude. Solid circles represent events with focal depth larger than 200 m and open circles indicate events with focal depth shallower than 200 m.

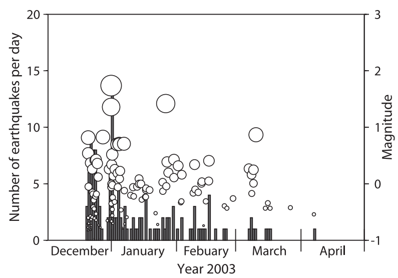

Fig. 7 Full-time series for the 2002–2003 Tricastin earthquake swarm. Histogram shows daily number of earthquakes detected by station CLAN. An M_L magnitude was computed for events that could be located (plotted as circles with radii proportional to the magnitude); some smaller events recorded at CLAN were also assigned a magnitude under the assumption that the focus was right beneath the station. Note that, although monitoring continued till August 2003, no event could be located later than April.

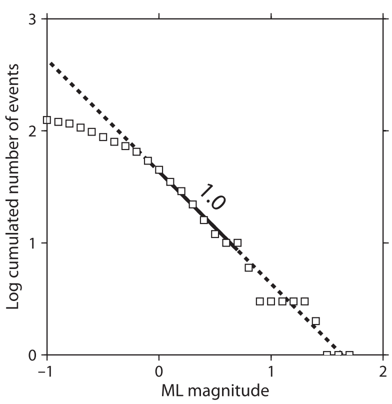

Fig. 8 Cumulated frequency–magnitude distribution for the 130 events of the series yields a Gutenberg–Richter *b*-value of 1.0 ± 0.3.

Earthquake populations are classically characterized by the Gutenberg–Richter law (Gutenberg and Richter, 1956)

$$\log_{10} N = a - bM,$$

where N is the number of earthquakes with magnitudes larger than or equal to M. Figure 8 shows the frequency–magnitude distribution for the 130 events of the magnitude series. The deviation from the Gutenberg–Richter law for negative magnitudes obviously results from our catalogue being incomplete for small-magnitude earthquakes. The b value of 1.0 ± 0.3, a figure similar to that found for the western Alps as a whole (0.95 ± 0.03), was estimated by a maximum-likelihood analysis (Aki, 1965; Utsu, 1966). The large uncertainty for b partly results from the Tricastin series being limited in size, but also from significant variation with time: if we split the time series into two and analyse its two halves, b decreases from 1.2 ± 0.4 at the beginning of the swarm ('deep' events) to 0.8 ± 0.3 at its termination (events shallower than 0.2 km).

Discussion and conclusions

No fault has ever been mapped at the surface where the approximately N–S-trending, *c*. 5-km long, 0- to 1-km deep rupture zone imaged by the 38 relocated events was identified. One reason is that most brittle Lower Cretaceous series that could be used as tectonic markers are obliterated in the study area by looser sediments. However, we mentioned that seismic exploration recognized several Upper Miocene N–S-striking faults in the Rhône Valley and that electric exploration reveals extensive fracturing of the top of the Urgonian slab. N–S-oriented topography in the central part of Fig. 2 between Clansayes and Valaurie can also be noticed. The identification of such a widespread rupture zone instead of a pinpointed focal zone can explain the impression of migrating events reported by inhabitants during episodes of the past centuries.

The main peculiarity of the Tricastin swarm is its ultra-shallowness, other swarms being usually deeper-seated (Table 1). For station CLAN, we indeed observed S–P intervals of only 45 ms. If we assign a P-wave velocity of 5.3 km s^{-1} to the massive Urgonian limestone slab that outcrops 1.5 km from CLAN, and if we use a V_P/V_S ratio of 1.71, the hypocentral distance would be *c*. 300 m. This would be the focal depth value (relative to the surface) for a focus right beneath the station; a still shallower value would be obtained otherwise.

Half of the events occurred in the 0–200-m depth range (Fig. 5), which very likely corresponds to the 250-m thick Urgonian slab that outcrops nearby. Seismic foci also cluster 400 m below in the 400–600-m depth range, in the midst of the Lower Cretaceous sediments where relatively

Table 1 Mean depth for a selection of instrumentally studied earthquakes swarms. Depth is referred to the surface where the source text is explicit about surface elevation, assumed to be referred to the surface otherwise.

Location	Date	Mean depth (km)	Reference
Imperial Valley, California (USA)	1975	6	Johnson and Hadley (1976)
Reykjanes Peninsula (IS)	1972	3.5	Klein *et al.* (1977)
Arkansas (USA)	1982	5.5	Chiu *et al.* (1984)
Remiremont, Vosges (F)	1984–1985	7	Haessler and Hoang-Trong (1985)
Mammoth Mt., California (USA)	1989	7.5	Hill *et al.* (1990)
Steigen, Nordland (N)	1992	6.5	Atakan *et al.* (1994)
Crested Butte, Colorado (USA)	1986	6.5	Bott and Wong (1995)
Izu Peninsula, Honshu (J)	1997	4.5	Aoki *et al.* (1999)
Manchester (GB)	2002	2.5	Baptie and Ottemoeller (2003)
Colfiorito, Umbria-Marche (I)	1997	6	Chiaraluce *et al.* (2003)
Vogtland/NW Bohemia (D/CZ)	1985–2001	8.5	Fischer and Horálek (2003)
Mt. Hood, Oregon (USA)	1980–2002	4.5	Saar and Manga (2003)
Campi Flegrei, Campania (I)	2000	2	Bianco *et al.* (2004)
Usu Volcano, Hokkaido (J)	2000	5.5	Zobin *et al.* (2005)
Mt. Hochstaufen, Bavaria (D)	2002	2	Kraft *et al.* (2006)
Ubaye, western Alps (F)	2003–2004	7	Jenatton *et al.* (2007)
Obsidian Buttes, California (USA)	2005	5	Lohman and McGuire (2007)
Tricastin, Rhône Valley (F)	2002–2003	0.5*	This study

*With 50% of events in the 100–300-m depth range.

CZ, Czech Republic; D, Germany; F, France; GB, Great Britain, I, Italy; IS, Iceland; J, Japan; N, Norway; USA, United States of America.

rigid limestones alternate with marls. A third cluster is sited at a depth of about 1000 m. This is precisely where another rigid limestone slab can be expected in the stratigraphy (the so-called Tithonian facies characteristic of Upper Jurassic series in southeast France). Thus, the upper and lower clusters occurred in brittle limestone slabs and the intermediate cluster in a relatively rigid part of the series.

We could not evidence any migration of epicentres with time for the beginning of the swarm (before 1 February 2003), when only the central part of the rupture zone was active (Fig. 6). After that date, activity seems to have spread southwards and northwards by several kilometres. We probably lack a detailed description of the swarm at earlier times (i.e. in December 2002) to understand this phenomenon. As a result of its suddenness, it cannot be attributed to fluid diffusion from a *single* source point, as is sometimes observed for other deeper swarms (see, e.g. Hainzl and Fischer, 2002; Daniel *et al.*, 2009).

Figure 6 also shows that, before 1 February 2003, the swarm involved 'deep' earthquakes (with focal depths larger than 200 m). In contrast, all later earthquakes but three clustered in the first 200 m. Thus, the extension of seismic activity we observed along the rupture zone in the last part of the swarm series was accompanied by the upward migration of seismic foci. This difference between the two halves of the swarm series can also be evidenced with regard to the *b* value, which decreased from 1.2 (deeper, earlier events) to 0.8 (shallower, later events). Hainzl and Fischer (2002), when analysing the Vogtland/NW Bohemia swarm, that is in contrast much deeper (8.5 km), also observed similar *b*-value variations.

As past swarm episodes that were marked by detonation-like sounds, the 2002–2003 Tricastin earthquake swarm was noticed for its many felt events. This can be surprising for magnitudes that did not exceed 1.7. However, a recent study in the southern French Jura (Thouvenot and Bouchon, 2008) showed that earthquakes sited at a depth of *c*. 900 m could be felt even for negative magnitude values (down to magnitude −0.7). In Tricastin, as all relocated events but two have magnitudes larger than −0.7, and as focal depths are much shallower, practically all shocks could have been felt or – more probably – heard.

Finally, as with all earthquake swarms, the most puzzling problem remains that of the initiation and duration of the phenomenon. In Tricastin, just like in Ubaye, there is an interesting common belief that earthquake swarms are often the consequence of flooding. Seasonal groundwater recharge and rainfall have effectively been described as triggering agents for some swarms (e.g. Saar and Manga, 2003; Kraft *et al*., 2006; Husen *et al*., 2007). Miller (2008) theorized that 'unambiguous rain-triggered seismicity will only occur in karst regions'. This hypothesis is appealing in our particular case because, where exposed in southeast France, the Urgonian slab indeed presents karstic features. However, daily rainfall at the nearby Montélimar weather station (Fig. 9) does not reveal any exceptional variations prior to the observed swarm activity. In September 2002, the catastrophic storm that swept the Avignon region, 50 km to the south of Tricastin, and whose rainfall is held by Rigo *et al*. (2008) as responsible for an increase in seismicity rate on faults between Nîmes and Avignon cannot be traced in Fig. 9, probably because of its local – although devastating – character. Unless we hypothesize that the weather station used here and situated 20 km to the north missed a similar heavy rain episode in Tricastin, we

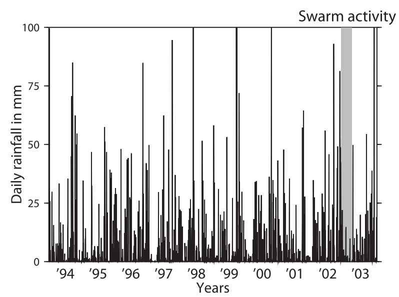

Fig. 9 Daily rainfall at Montélimar weather station (Météo-France), 20 km north of Tricastin, over a 10-year period (1994–2003). Daily rainfall exceeded 100 mm several times over this period (1994, 1998, 1999, 2000 and 2003), with a maximum in autumn 1999 (*c*. 220 mm), but no triggered seismic activity was ever detected in Tricastin. The 2002–2003 earthquake swarm follows a rainy episode very similar to other autumnal heavy rain events.

still lack any clear triggering phenomenon that could explain why Upper Jurassic and Lower Cretaceous series can be healed for so many tens of years before suddenly bursting out in a veritable cannonade.

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