



Underlying Châteauneuf-du-Pape is a salt diapir and the still active Nîmes Fault of southeastern France

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Abstract

The shallow earthquake of November 11, 2019, at Le Teil and the catalogue of historic seismicity in the SE Basin, together record diffuse seismicity along high-angle faults associated with rift structures of the Tethyan margin. In addition to several evidences of Quaternary surface co-seismic ruptures, archeogeological data suggest at least one highly damaging earthquake in Roman times. Regional seismic profiles currently help define the complex tectonic structure and the Plio-Quaternary slip history of these faults. The surface trace of these faults is not connected to off-sets in the basement level owing to several decollement levels within the Triassic salt, deeper Carboniferous coal measures and shallower Jurassic and Cretaceous black-shale horizons. Analogous to the Northern Apennines, brittle failures along the faults of the SE Basin may occur only within the deep crystalline basement and shallow carbonate layers, while salt and shale horizons deform ductily. In this context, the salt diapir beneath the Châteauneuf-du-Pape has caused progressive uplift and bending of alluvial terraces throughout the Quaternary. These faults pose a potential danger to nuclear plants and several cities. Regional deep seismic profiles would be required to define the architecture of the fault system within the infra-Triassic substratum. The acquisition of high resolution seismic profiles in the areas where these faults are covered by thick Plio-Quaternary deposits would also provide data to date and quantify the successive episodes of fault reactivations and deformations. Long-term GPS measurements within the different fault blocks also would be required to quantify both the vertical and horizontal motion of each block relative to the others. Ultimately, a denser seismological network is needed to properly locate the focal mechanisms at depth and plot them on an accurate 3D structural model of the regional fault system.

Keywords French SE Basin · Fault trajectory · Fault reactivation · Seismic hazard

1 Introduction

Due to the lack of significant hydrocarbon discoveries in the SE Basin (Fig. 1), its regional seismic coverage has remained limited to a few localized exploration blocks in the Manosque (Valensole exploration block operated by Total; Roure et al. 1986a, b), Pic-St-Loup (Languedoc-Nord exploration block operated by Total; Briend et al. 1985, 1987; Roure et al. 1986a, b), La Clappe-St-Chinian and Alès areas (Languedoc-Nord and Alès exploration blocks operated by Elf-Aquitaine; Layotte and Ricarte 1988a, b, 1989; Roure

et al. 1988, 1992, 1994), and to widely spaced reconnaissance surveys supported by the FSH -Fond de Soutien aux Hydrocarbures—along the Rhône Valley and adjacent foothills in the Diois and Baronnies (Roure et al. 1986a, b, 1992, 1994; Le Pichon et al. 2010; Rangin et al. 2010). Therefore, our understanding of these faults is limited to mapping surface traces, while subsurface architecture currently is poorly understood.

Inherited from the Permian collapse of the Hercynian orogen and subsequent Triassic and Liassic episodes of extension, these faults were locally reactivated during Late Cretaceous–Eocene compressional episodes associated with the Pyrenean orogeny. These were again reactivated during Neogene Alpine compressions, in the eastern part of the basin in vicinity of the Durance Fault.

The regional seismic catalogue points towards a diffuse seismicity along most of these faults, but, no scientific consensus exists yet on the rates and degree of Neogene to

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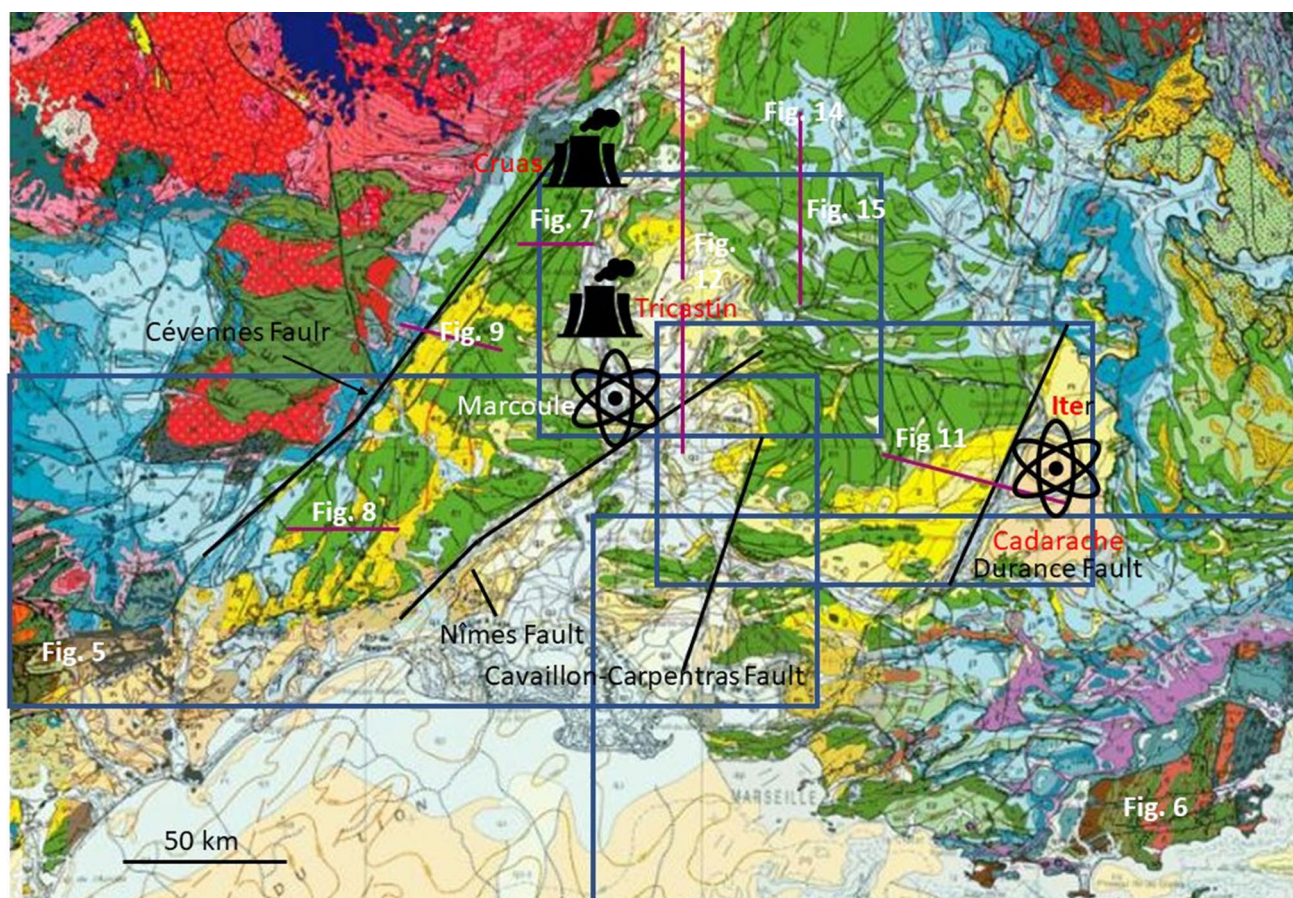


Fig. 1 Regional geological map outlining the location of the SE Basin (extract from the Geological map of France, 1/250.000 scale, BRGM, online on Geoportail). Notice the location of the Durance,

Nîmes and Cévennes faults, the Châteauneuf-du-Pape vineyard, the location of seismic profiles and more local maps imaged on the other figures

Quaternary reactivation of the Cévennes and Nîmes faults farther to the west (Fig. 2; Sapin and Hirn 1974; Combes 1984; Ritz 1991; Carbon et al. 1993; Combes et al. 1993; Grellet et al. 1993; Blès et al. 1995; Ghafiri 1995; Jomard et al. 2017; Sébrier et al. 1997, 1998; Lacassin et al. 1998; Peulvast et al. 1999; Baroux et al. 2001; Mattauer 2002; Schlupp et al. 2001, 2002; Séranne 2002; Quenet et al. 2004; Rigo et al. 2008; Terrier et al. 2008a, b; Castelli et al. 2012; Bellier et al. 2021). In this context, the shallow earthquake of November 11, 2019 at Le Teil, near the nuclear plant of Cruas (Fig. 1), points towards our lack of subsurface knowledge at regional scale (Ritz et al. 2020; Le Dortz et al. 2021).

Because we recognized the Quaternary activity of a salt diapir and Nîmes Fault beneath the Châteauneuf-du-Pape vineyard (Fig. 1) during a wine-and-geology tour just a few weeks before Le Teil earthquake, this paper aims to convince not only the scientific community but also the nuclear industry and public agencies for the need to properly image the subsurface architecture of these faults in areas where they are still covered by Plio-Quaternary deposits. The deformation of

younger strata are likely to provide additional means to date and quantify their recent activity.

2 Timing of the main episodes of deformation and evidences for post-Miocene reactivations

The SE Basin records a long succession of extensional and compressional episodes, from the Late Paleozoic to the Present. Intra-crustal weaknesses associated with successive Permian, Tethyan and Oligocene extensional episodes control the structural grain of the region, accounting for the localization of major Paleogene and Neogene inversions, as well as incipient Quaternary reactivations.

2.1 Permian collapse, Triassic–Jurassic Tethyan rifting, and the West European Oligocene rift system

Three main extensional episodes impacted Western Europe, thus contributing to the overall architecture of the

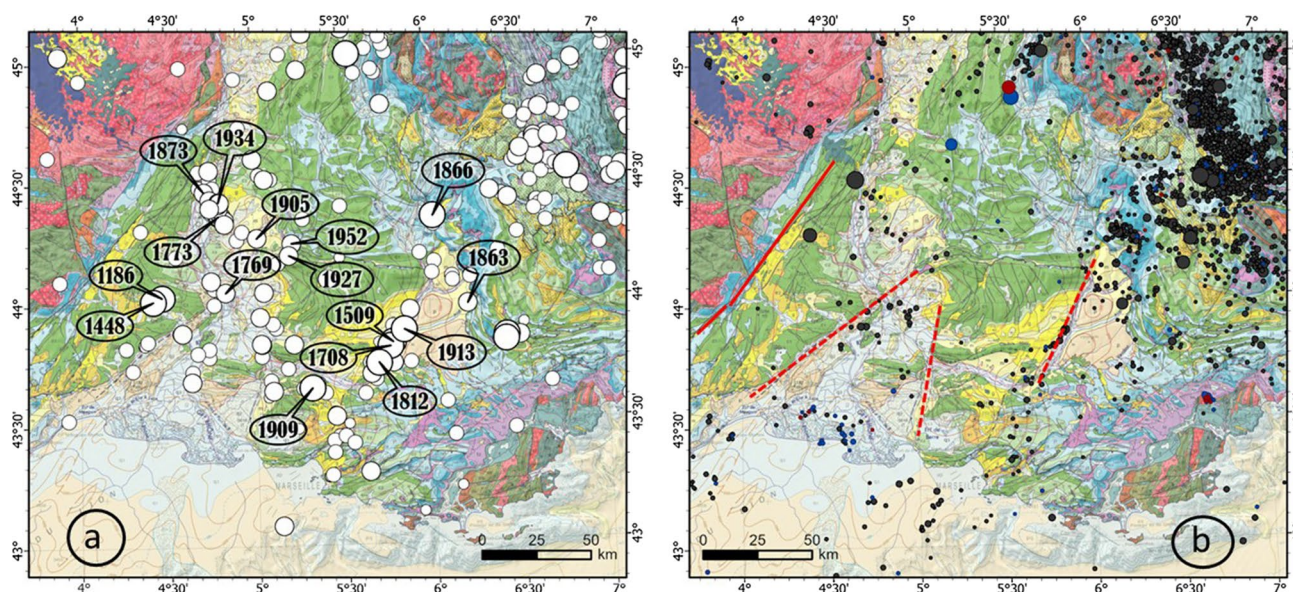


Fig. 2 **a** Distribution of some historical earthquakes in the SE Basin (after Larroque et al. 2021). **b** Epicenter map of major recent earthquakes in the SE Basin (after Larroque et al. 2021)

basement and lateral thickness variations within its sedimentary cover. They affected the deposition of numerous ductile layers such as coal measures, salt and blackshale horizons, which are interbedded with more brittle carbonate layers within the composite sedimentary infill of the SE Basin (Fig. 3).

2.1.1 Permian collapse of the Hercynian orogen

As observed along the deep seismic Ecors profile across the Paris Basin, the Moho is relatively flat beneath the former Hercynian orogen between the British Channel and the Pyrenees, with no evidence of any residual crustal root (Cazes and Torreilles 1988; Roure et al. 2010a, b). Seemingly, the

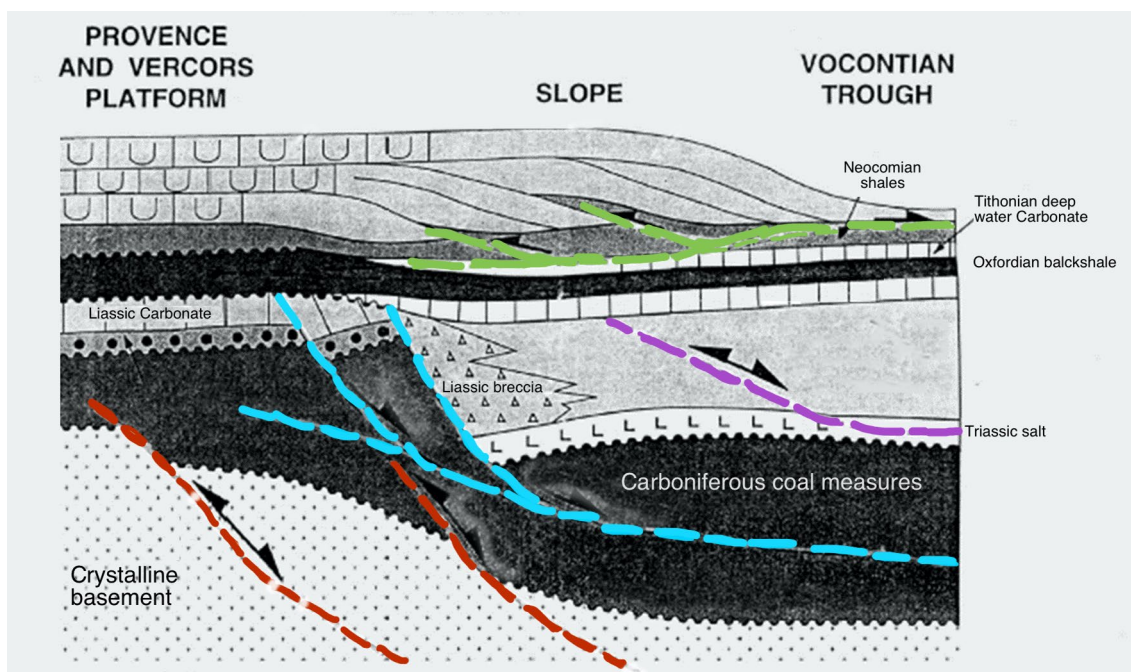


Fig. 3 Synthetic lithostratigraphic column and potential decollement levels of the SE Basin

basal unconformity of the Mesozoic series overlying the Paleozoic strata remains parallel to the Moho, not only beneath the Paris Basin but also in the Aquitaine foreland of the Pyrenees, as expressed by the deep seismic records of the Ecors Pyrenees profile (Fig. 4; Choukroune and Ecors Team 1989; Roure et al. 1989; Roure et al. 2010a, b; Roure and Colletta 1996).

All the lower crust is layered beneath Western Europe (Bois 1992; Roure et al. 2010a, b). This reflects post-Hercynian stretching and thinning of the crust, coeval with the negative inversion of former Hercynian thrusts (Echter and Malavieille 1990). The stretching and thinning of the crust

causes the development of half grabens that are filled with continental Permian strata.

Well imaged on the Ecors Pyrenees profile (Fig. 4; Choukroune and Ecors Team 1989; Roure et al. 1989; Roure et al. 2010a, b), Permian basins are also exposed at the surface in the Lodève Basin in Languedoc, and in the Maures and Esterel massifs in Provence (Figs. 5, 6; Roure et al. 1992, 1994; Toutin-Morin and Bonijoly 1992; Roure and Colletta 1996). The subsurface extent of the Permian basins beneath the Mesozoic sedimentary infill of the SE Basin has been recognized by both conventional seismic

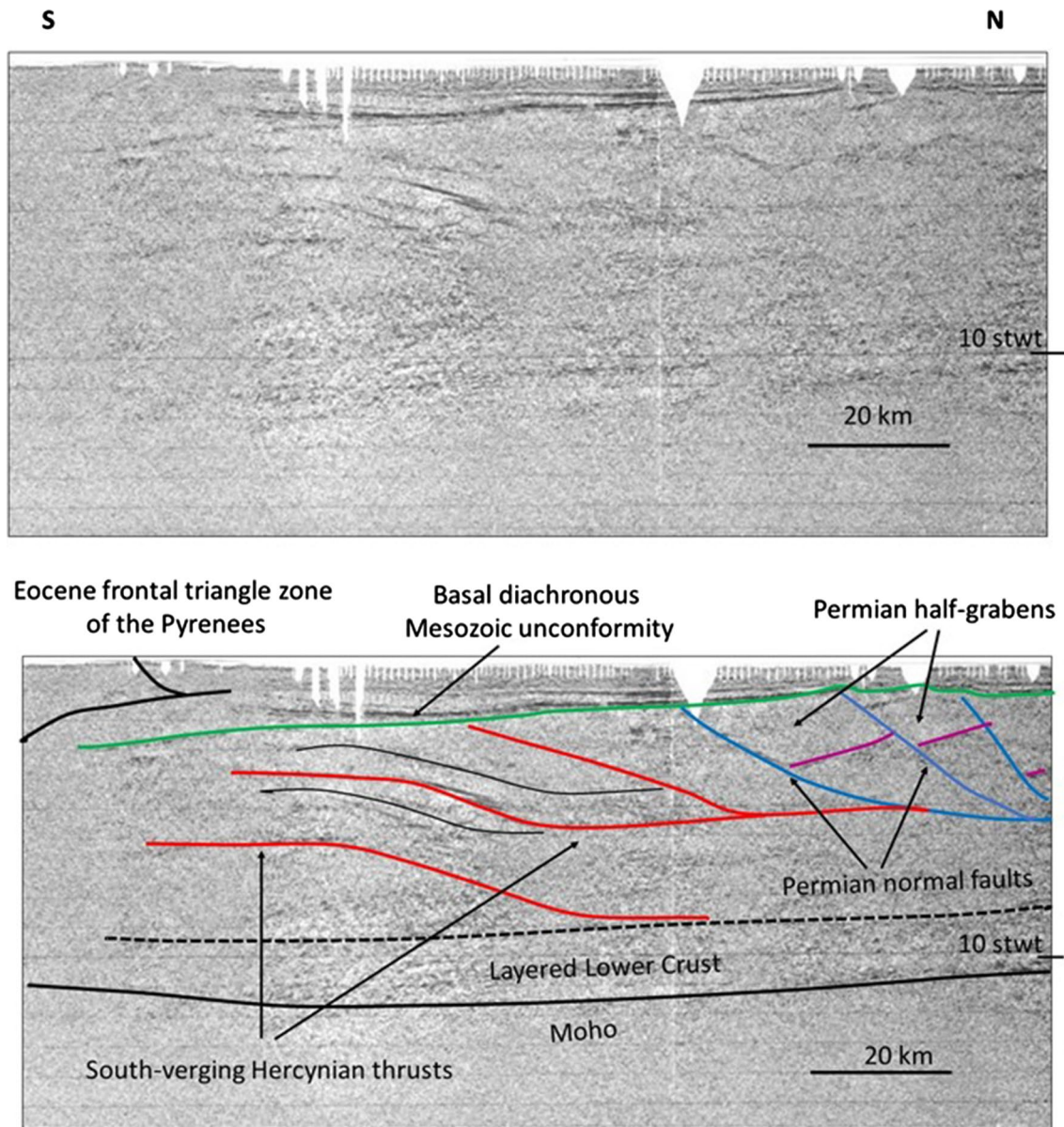


Fig. 4 Uninterpreted (top) and interpreted (bottom) NS Ecors seismic profile crossing the Aquitaine foreland of the Pyrenees. Notice the dominantly isopachous and gently flexed attitude of the Western European crust, its Moho remaining parallel to the basal unconform-

ity developed at the top of Paleozoic series during the Mesozoic to Cenozoic times. Notice also the south-verging Hercynian thrusts, and the Permian collapse basins, controlled by the negative inversion of former thrusts

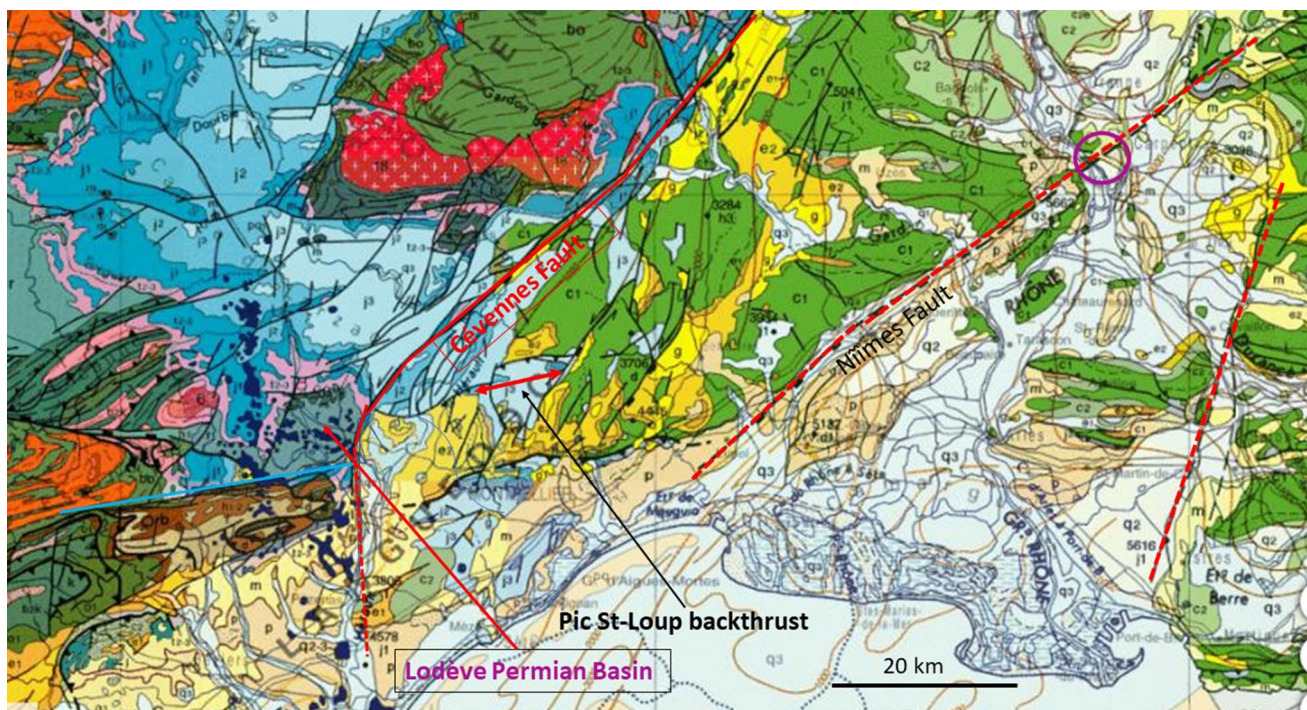


Fig. 5 Regional geological map outlining the distribution of Permian basins in the outcrops of the Lodève Basin and in the subsurface of the Pic St-Loup area, in the vicinity of the Cévennes Fault in the western part of the SE Basin (extracts from the Geological Map of

France at 1/250.000 scale, BRGM, online on Géoportail). Notice the left-lateral offset of these basins, due to Pyrenean—Late Cretaceous to Eocene—transcurrent reactivation of this fault during N-trending compressions

imagery and by wells in the vicinity of the Pic St-Loup north of Montpellier and between the Ste-Victoire and Ste-Baume massifs in Provence (Roure and Colletta 1996). These basins are in direct continuity with the Lodève and Maures outcrops, respectively.

Limited by north-dipping normal faults branching on former south-verging Hercynian thrusts in Aquitaine, the structure of these Permian basins are controlled by steep EW-trending north-dipping normal faults in the Lodève and Pic St-Loup areas, as well as EW-trending high-angle faults in Provence. However, unlike in Aquitaine, no deep seismic profile is currently available in Languedoc nor in Provence to determine whether or not these Permian faults are also rooted on the former Hercynian thrust system.

Nonetheless, these EW-trending Permian faults constitute a major regional element controlling the overall structural grain both in Provence and Languedoc. Their subsequent Pyrenean and Alpine inversions have controlled and localized most compressional structures in the overlying Mesozoic sedimentary cover, i.e., the Pic St-Loup in Languedoc, Ste-Baume and Ste-Victoire structures in Provence, and possibly the Alpilles, Luberon and Ventoux-Lure trends farther to the north.

2.1.2 Triassic and Jurassic Tethyan rifting

The NE-trending Cévennes and Nîmes faults in the west and the Durance Fault in the east were mainly active during the Triassic and Liassic rifting episodes of the Tethys (Beaudrimont and Dubois 1977). They are only locally imaged by seismic profiles and they constitute one of the main controls on the lateral thickness and facies variations in the SE Basin (Fig. 3). Smaller faults trending in the same direction in the Ardèche margin, i.e., the Uzer Fault, are sealed by the Upper Jurassic and Cretaceous post-rift sequences (Fig. 7; Giot et al. 1991; Bonijoly et al. 1996).

2.1.3 The West European rift system and opening of the Western Mediterranean Basin

Following the Pyrenees and Western Alps Ecors profiles, two other important deep seismic profiles were shot across the Rhine Graben in the north (Brun et al. 1991, 1992), with the collaboration of the German Dekorp programme, and another, marine one, in the Gulf of Lion in the south (Gorini et al. 1991, 1993 and references therein). These correspond

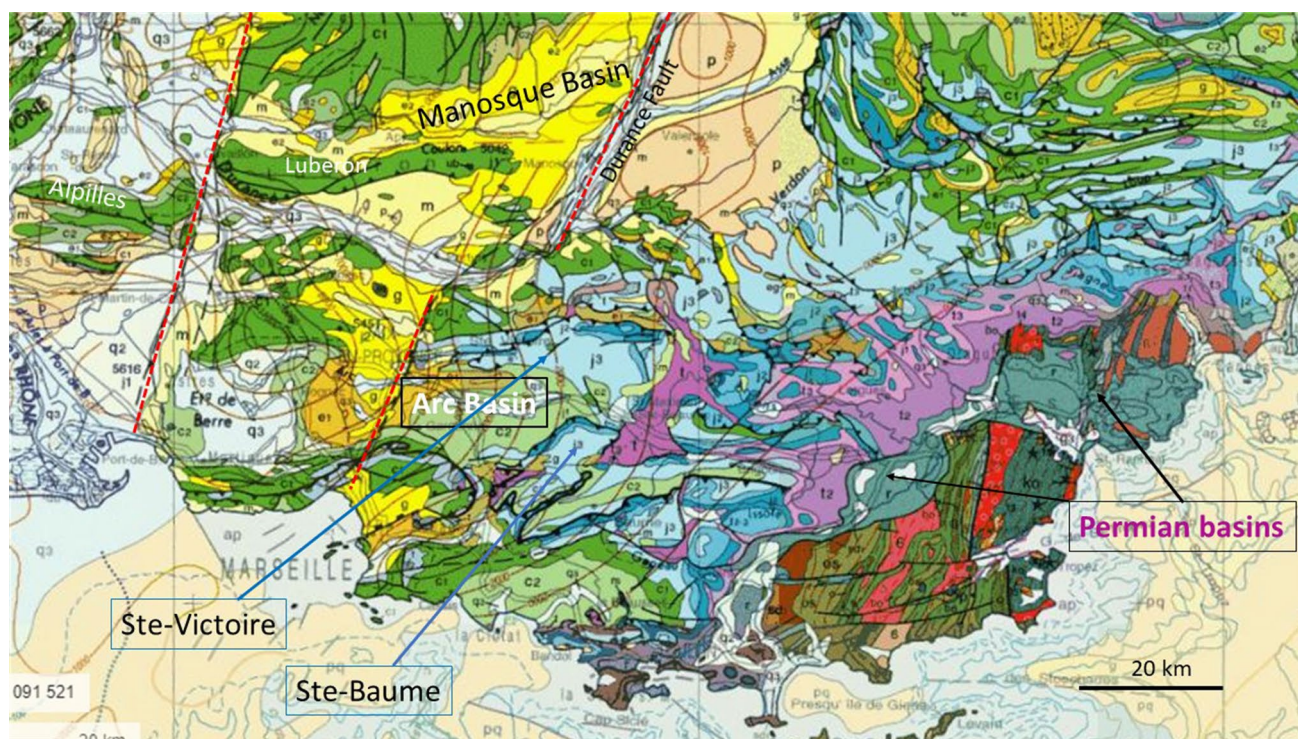


Fig. 6 Regional geological map of the Permian basins exposed at the surface in the Maures and Esterel, in eastern Provence, and their westward subsurface extension beneath the Arc Basin, between the Montagne Ste-Victoire and the Ste-Baume thrust systems, respec-

tively located north and south of the Arc Basin (extracts from the Geological Map of France at 1/250.000 scale, BRGM, online on Géoportail)

to two adjacent segments of the Western European Oligocene rift system.

Due to the lack of deep seismic profiles in the SE Basin, we still do not know how the Mesozoic and Oligocene extension has been accommodated within the infra-Triassic substratum.

Nevertheless, a French-Chinese team (Cifalps; Lu et al. 2020) has recently recorded a regional crustal profile from the Alps to the Massif Central, thus crossing the entire SE Basin, by means of passive seismic recording and tomography, whereas the still ongoing Alpararray project will illuminate the lithosphere architecture of the entire Western Alpine realm (Nouibat et al. 2021). Fortunately, the Cifalps crustal velocity profile was a success, documenting for the first time the cumulative Jurassic and Oligocene crustal thinning and shallowing of the Moho beneath the SE Basin.

As mentioned earlier, many Oligocene normal faults in the SE Basin are rooted in the Triassic evaporitic layers, and we do not yet have enough regional seismic profiles to document more precisely the location of the Oligocene extension in the underlying basement, nor the current attitude of the lower crust, Moho surface and lithospheric mantle beneath this basin.

Conventional seismic profiles recorded by Elf-Aquitaine and IFP in the Saint-Chinian and La Clappe area in

Languedoc document the local negative inversion and collapse of north-verging Pyrenean thrusts during the Oligo-Miocene opening of the Gulf of Lion (Roure et al. 1988; Gorini et al. 1991; Séranne et al. 1995).

Furthermore, industry profiles and wells in the Manosque and Vauvert areas, close to the Durance Fault in the east and Nîmes Fault in the west, provide control on the location and architecture of shallow salt domes made up of Oligocene salt. These salt deposits have been used locally for gas storage.

2.2 Late Cretaceous–Eocene Pyrenean and Neogene Alpine compressional episodes

As described below, the basal Triassic evaporitic decollement level has been extensively remobilized during Pyrenean and Alpine compressions in the Diois and Baronnies foothills, together with shallower Liassic, Oxfordian and even Neocomian shale horizons (Fig. 3).

Elsewhere, in Provence and Languedoc, EW and NE-SW-trending high-angle basement-involving faults inherited from Permian and Tethyan rifting have induced localized foreland inversions. Inferred from seismic imagery and analogue models, the Pic St-Loup, Ste-Victoire, Ventoux-Lure and La Lance structures are interpreted as

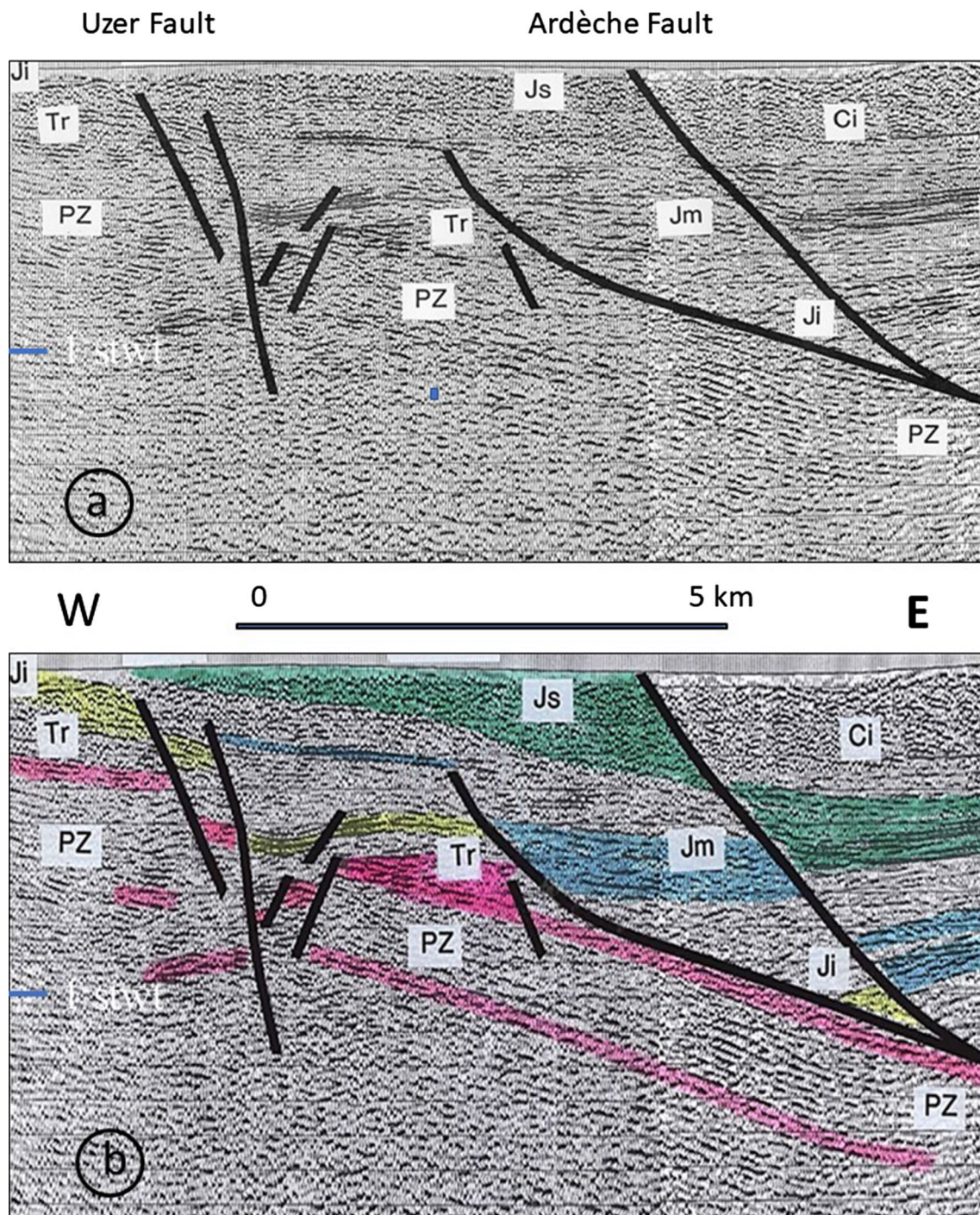


Fig. 7 Seismic profile across the Ardèche margin, outlining the listric attitude of the Ardèche Fault in the east, and the Jurassic basement-involving Uzer Fault in the west, which is sealed by Upper Jurassic and Cretaceous post-rift sequences. See location on Fig. 1

triangle zones, related to crocodile or wedging tectonics (Roure et al. 1994). These structures are associated with shallow north-verging thrust faults, antithetic to the underlying basement fault. We suspect the same for the Luberon and Alpilles trends but this is highly speculative without seismic profiles.

Le Pichon and Rangin proposed regional tectonics of gravitational gliding on a salt layer (Le Pichon et al. 2010; Rangin et al. 2010). This hypothesis was inferred from a basement map that did not display the regional Jurassic nor Permian basement-involving extensional faults. Also, their inferred thickness of the Triassic salt was not correct.

Alternatively, we believe Neogene and younger deformation of the Mesozoic cover reflects compressional episodes involving local reactivation of deeper basement faults.

Horizontal slickensides are also common along formerly normal NE-trending high-angle Mesozoic and Oligocene faults planes at places where they are cropping out, and account for successive left-lateral and right-lateral transpressional episodes. These record episodes of Pyrenean NS compression and Alpine NW–SE compression, respectively.

2.3 Post-Miocene reactivations

Detailed studies of recent seismicity provide first order records of recent and diffuse reactivations on the major regional high-angle faults (Fig. 2; Larroque et al. 2021). Unfortunately, these publications do not provide accurate information on the depth of focal mechanism. Thus we do not know how the faulting relates to brittle failure in the Mesozoic carbonate cover or infra-Triassic basement.

A short-term monitoring was carried out by IRSN over ten years along the well imaged Durance Fault, near Cadarache and ITER sites (Volant et al. 2000; Dervin et al. 2007; Cushing et al. 2008, 2014).

An archeogeological record documents the reactivation of the Nîmes Fault in Roman times (Combes and Paillet 1997; Fiches et al. 1997; Granier and Combes 1997; Combes et al. 1998; Volant et al. 2009). Nonetheless, long term regional records are insufficient to determine recurrence intervals between two successive damaging events and insufficient to determine the maximum possible magnitude of such earthquakes.

Local paleoseismological and sedimentological studies have also been performed on the Pio-Quaternary sediments. A trench in the Pleistocene gravels, on the flanks of the Etang Salé collapse ring, provides evidence of low-angle reverse faulting that likely corresponds to compressional tectonics and Quaternary doming of the Châteauneuf-du-Pape diapir (Carbon et al. 1993; Combes et al. 1993; Bellier et al. 2021).

Shallow magnetotelluric and seismic profiles and wells records map out coarse-grained sediment in a Messinian canyon and associated drainage channels of the Rhône River (Roure et al. 2007). The resolution, however, is insufficient to trace second-order deformation features.

Miocene strata are tilted towards the south on the southern flanks of La Lance and Ventoux anticlines in the north. Pliocene strata are involved in the east-dipping monocline adjacent to the Durance River in the east. These structures account for the active inversion of the entire North Provençal tectonic block.

Finally, the Durance River has been also diverted from its initial trajectory during the Pleistocene. When rounded pebbles were deposited in the Crau Plain south of the Alpilles,

the Durance River was flowing directly towards the Mediterranean. The river now runs westwards north of the Alpilles and joins the Rhône River just south of Avignon, due to the recent tectonic uplift of the Lamanon corridor (Champion et al. 2000; Clauzon et al. 2011). Although no seismic data are yet available in this area, this tectonic uplift could be associated with (1) the reactivation of basement faults along the southern flank of the Alpilles, (2) the 1909 earthquake of Lambesc (Baroux et al. 2003; Chardon and Bellier 2003; Chardon et al. 2005; Bonnet-Vidal and Bellier 2009), (3) rejuvenated topography, and recent uplift of the Messinian erosional surface in the eastern part of this range (Clauzon et al. 2011).

3 Seismic data and overall architecture of the fault system in the SE Basin

Due to the occurrence of Carboniferous coal measures, Triassic salt and Jurassic and Cretaceous shales, that operate as potential decoupling horizons in the SE Basin (Fig. 3), the surface trace of the Mesozoic and Oligocene faults cannot be extrapolated easily from the surface to the basement.

3.1 The listric attitude of the Corconne Fault

For the first time the listric attitude of an Oligocene normal fault was noted in an exploration block operated by Total near the Pic St-Loup (Briend et al. 1985, 1986, 1987; Roure et al. 1986a, b, 1988). There, the Corconne Fault is well exposed at the surface, dipping at high angle towards the east. At depth however, it becomes arcuate and even flat at the level of the Triassic evaporitic sequence, with no offset of the basement below its surface trace (Fig. 8; Roure et al. 1988; Séranne et al. 1995; Bénédicto et al. 1996).

3.2 The Uzer Fault, a synrift Jurassic fault sealed by the post-rift unconformity

During the Ardèche leg of the GPF -Géologie Profonde de la France- project, which aimed at drilling and coring the Triassic and Jurassic series on both sides of a synrift Liassic fault, they succeeded in recording a short seismic reflection profile running from the Ardèche Fault in the east almost to Largentière in the west. Taking the Corconne Fault as an analogue, this fault becomes listric at depth, the occurrence of Cretaceous strata still preserved in its footwall is evidence for a major post-Cretaceous, likely Oligocene offset.

Fortunately, however, another fault was imaged farther west on the newly recorded seismic profile, the Uzer Fault, which does not crop out at the surface (Fig. 7). It is obviously a basement-involving Jurassic fault, controlling lateral thickness variations in the Lias, and being sealed by

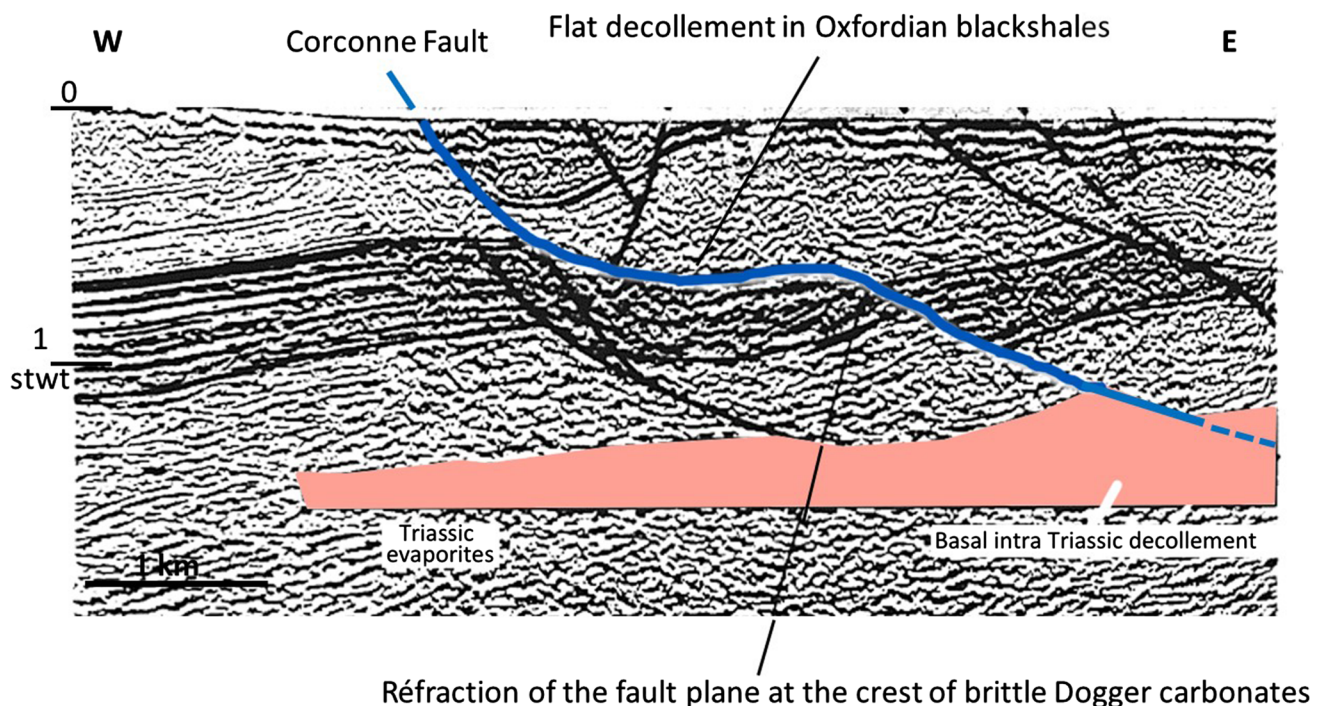


Fig. 8 Seismic profile across the Corconne Fault. Notice the listric attitude of this Oligocene normal fault, rooting within the Triassic evaporites (see location on Fig. 1; after Roure et al. 1988, modified)

unconformable Upper Jurassic and Cretaceous post-rift series (Giot et al. 1991; Bonijoly et al. 1996).

Rather than to drill on both sides of the Ardèche Fault, as initially planned by BRGM, they decided to drill on both sides of the Uzer Fault, thus securing the success and initial scientific goals of the project.

3.3 The high-angle Jurassic Cévennes Fault versus the listric Oligocene Cévennes Fault subsurface trajectories

Seismic profiles recorded by Elf-Aquitaine across the Alès Basin in a former exploration block provide a good control on the subsurface architecture of the basement and attitude of the Oligocene sedimentary infill in the direct vicinity of the surface trace of the Cévennes Fault (Roure et al. 1992, 1994; Sanchis and Séranne 2000).

Accurate mapping done by the BRGM in the hangingwall of the fault outlines younger-over-older tectonic contacts of the Mesozoic carbonates on top of underlying Carboniferous coal measures. Both the Triassic evaporites and underlying coal were thus acting as major décollement levels during extensional episodes.

A major east-dipping reflector is seismically imaged below the Oligocene depocenter at the foot of the surface trace of the Cévennes Fault. This reflector defines a major roll-over anticline that deforms the synrift Jurassic

and post-rift Cretaceous sequences of the former Mesozoic Tethyan passive margin (Fig. 9; Roure et al. 1992, 1994; Sanchis and Séranne 2000).

As evidenced by seismic records, the Alès Basin formation was controlled by a listric fault rooted in Triassic evaporites during the Oligocene extension. Mesozoic strata of the former hangingwall currently drape across the trace of the initial basement offset of the Cévennes Fault.

When restoring the section to its pre-Oligocene architecture, the former Liassic depocenter shifts towards the west. This implies there was an important offset of the basement at the current surface location of the Cévennes Fault during the Liassic rifting (Fig. 10).

3.4 The multistage evolution of the basement-involved Durance Fault and decoupling of its Mesozoic and Cenozoic cover

A relatively dense and overall good quality seismic survey was recorded by Total across its former exploration block in the Manosque Basin, along the Durance Fault (Briend et al. 1986; Roure et al. 1992; 1994). These profiles were subsequently reprocessed by Le Pichon's team at CEREGE, on behalf of CEA, a few years before the construction of ITER (Le Pichon et al. 2010; Rangin et al. 2010).

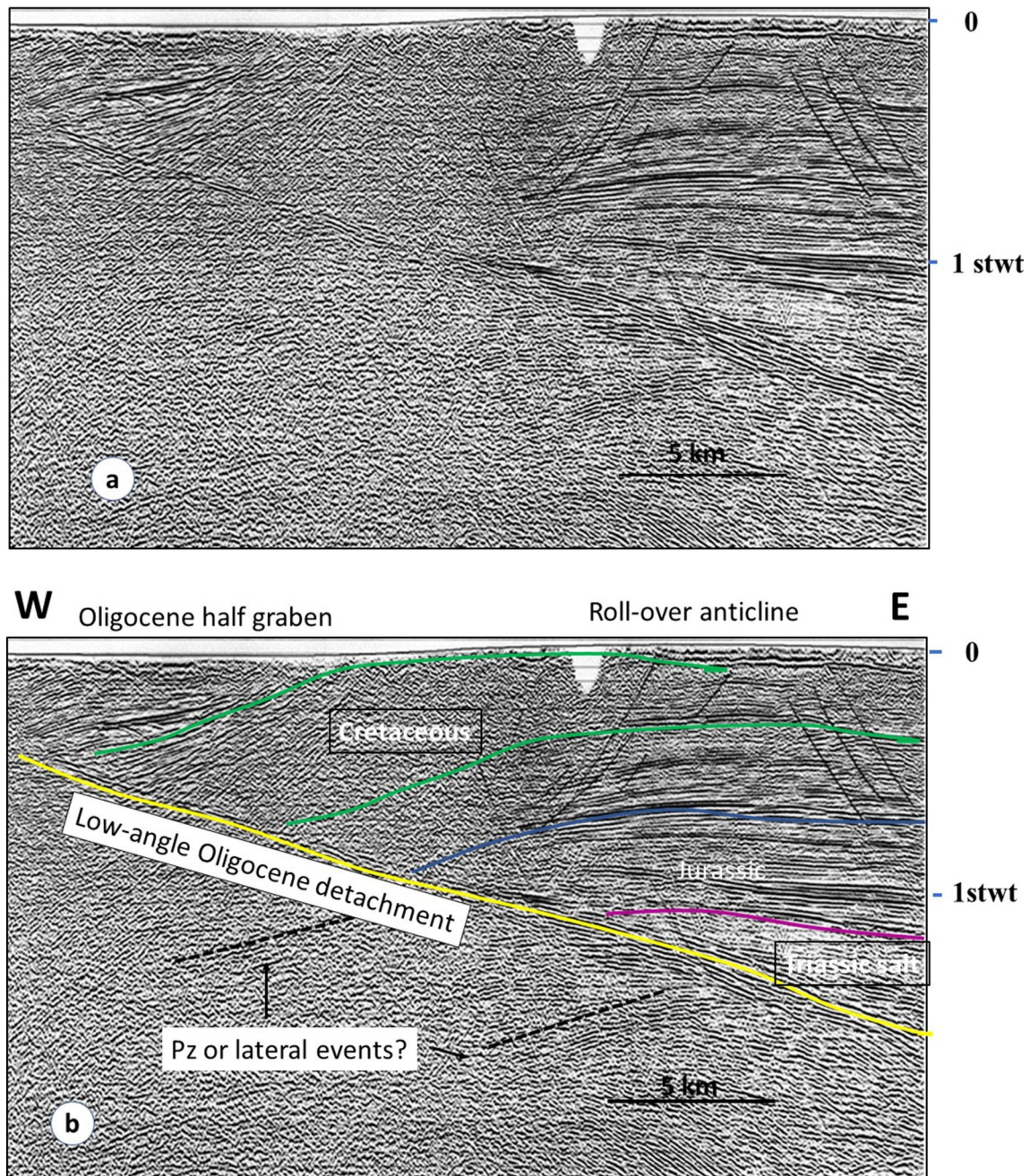


Fig. 9 Seismic profile crossing the Cévennes Fault and Alès Oligocene Basin. Notice the low angle attitude of the Oligocene Cévennes Fault, accounting for the development of a drag synformal half gra-

ben filled by Oligocene deposits in the west, and a roll-over anticline involving the main Jurassic to Cretaceous depocenter in the east (after Roure et al. 1992, modified)

Seismic interpretation associated to field studies helped us to better define the architecture of the Mesozoic and Cenozoic series both in the hangingwall and in the footwall of the Durance Fault, and to document its multistage reactivations (Fig. 11; Briend et al. 1986; Roure et al. 1992, 1994; Guyonnet-Benaize et al. 2015).

Despite the fact that an important vertical offset is observed in the basement, directly connected to the surface

trace of the fault, the sedimentary infill in the footwall has been obviously translated also laterally above the Triassic evaporites, i.e. towards the west, the south and the north, during the successive episodes of E-W extension (Triassic-Jurassic, Cenomanian, Oligocene), left-lateral Late Cretaceous-Eocene Pyrenean transpression, and right-lateral Neogene Pyrenean transpression.

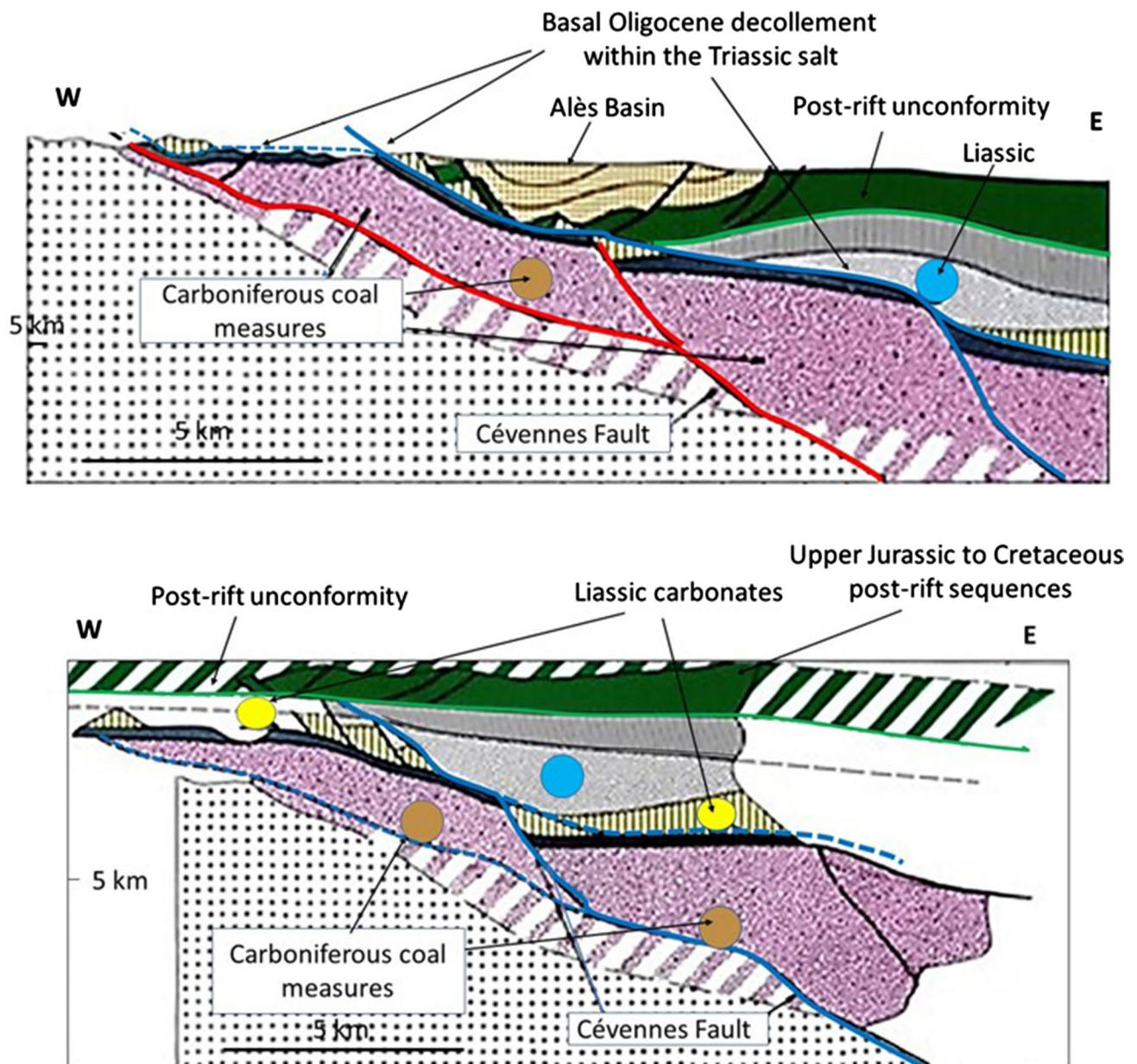


Fig. 10 **a** Current structural cross-section build from the interpretation of the same depth-converted seismic profile. **b** Restoration of the same cross-section at its Late Cretaceous stage, prior to the subse-

quent Oligocene rifting event. Notice the vertical offset required for the Jurassic Cévennes Fault to accommodate the thick Lower Jurassic synrift and Upper Jurassic to Cretaceous post-rift sequences

Analogue models have also been used to better understand the localization of the low-angle reverse faults observed within the Oligocene infill of the Manosque Basin, which nucleate near the crest of underlying Cenomanian grabens (Roure et al. 1992, 1994; Roure and Colletta 1996).

Ultimately, the Alpine inversion accounts also for the development of a shallow triangle zone and east-dipping monoclinial attitude of the Miocene to Pliocene deposits of the Durance Valley, parallel to the underlying basement fault.

3.5 Thick- and thin-skinned déformations associated to La Lance anticline and the Marsanne Fault

One spectacular seismic profile shot by the FSH (FSH-82SE-4) runs from the Valence Basin in the north to the Carpentras Basin in the south. It successively crosses the Cévennes Fault, the western closure of La Lance anticline and the Marsanne Fault, the Valréas Basin, the western subsurface extent of the Dentelles de Montmirail and underlying Nîmes Fault. However, only the central portion

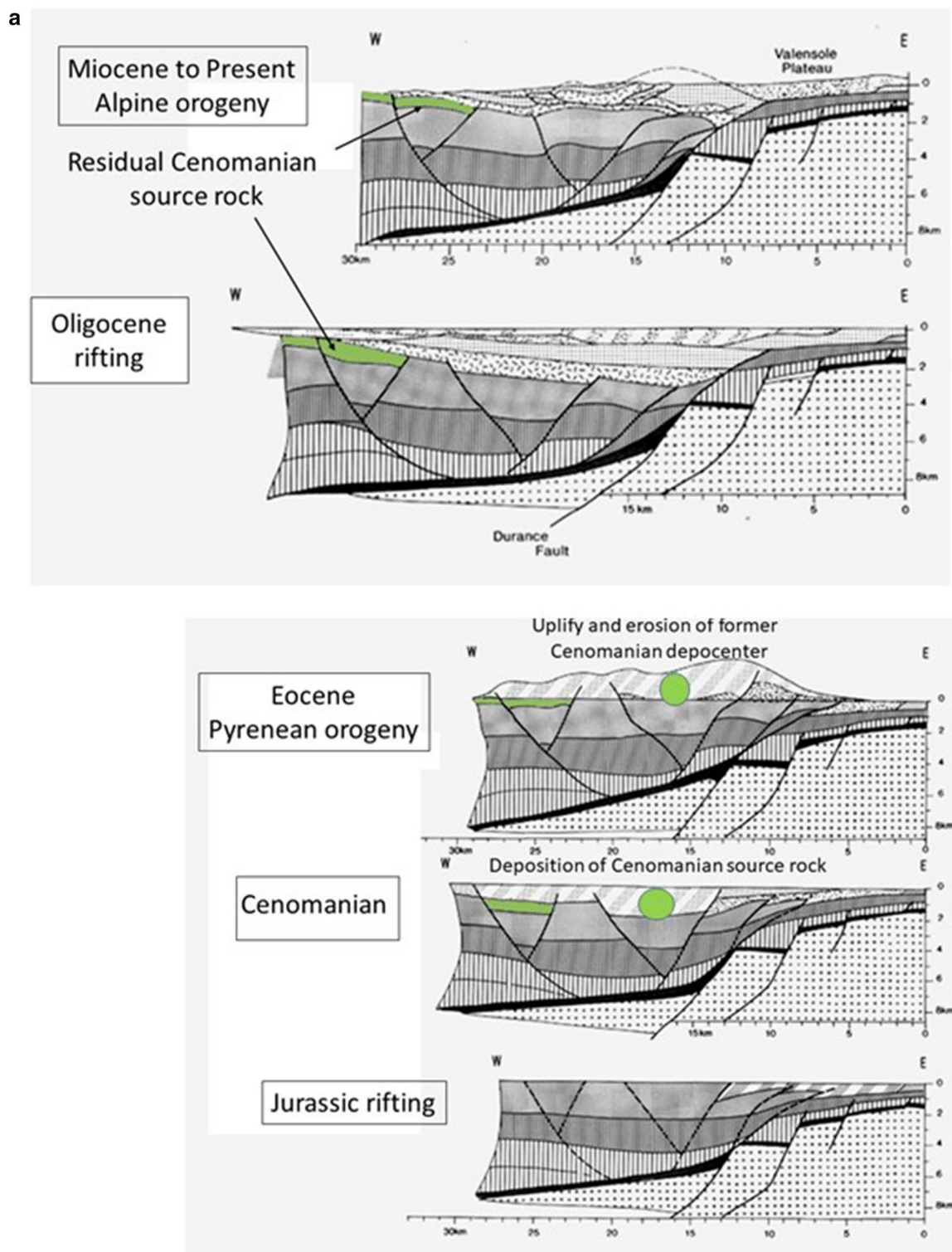


Fig. 11 a Serial structural cross sections crossing the Manosque Basin and Durance Fault, resulting from seismic interpretation and cross-section balancing (after Roure and Colletta 1996). Notice the Cenomanian source rock deposits (green color) still preserved in the distal part of the footwall of the Durance Fault, whereas they are totally lacking beneath the Oligocene synrift series in the proximal part of the footwall of the Durance Fault, as a result of their uplift and

erosion during the Pyrenean reactivation of this fault. **b** Serial tomographic sections of a sand box model aiming at reconstructing the evolution and successive positive and negative inversion of a complex half graben system (after Roure and Colletta 1996). Notice the localization of low-angle reverse faults in the Oligocene series, nucleating at the crest of Cenomanian normal faults

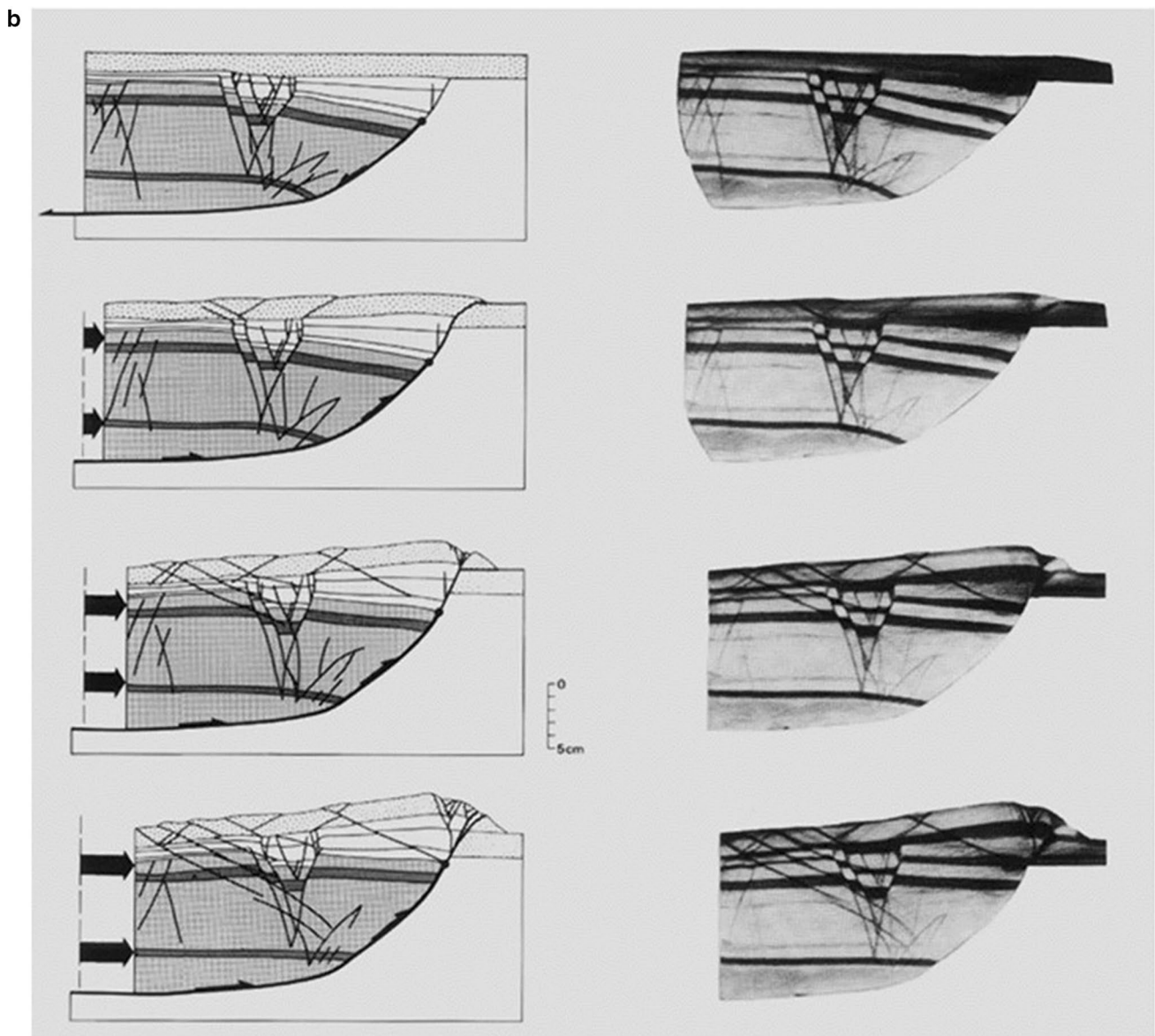


Fig. 11 (continued)

of this profile, i.e. La Lance anticline and Marsanne Fault, will be discussed in this paragraph, its southern part being used later, in the following section dedicated to the halokinetic structures associated to the Nîmes Fault.

At the surface, La Lance structure comprises a shallow north-verging ramp anticline and connects laterally with the Forêt de Saou syncline along a horizontal décollement propagating within Lower Cretaceous shales (Fig. 12). It carries on piggyback the paleoslope of the Urgonian Platform, as it is located at the former northern limit of the Barremian-Aptian Provençal shallow water paleogeographic domain in the south, and the deeper water shale series of the Vocontian Trough in the north (Roure et al. 1992, 1994).

At depth, the NW-trending La Lance anticline is underlain by a northeast-dipping antithetic normal fault in the basement, inherited from the Jurassic rifting. As La Lance anticline is located close to the southeastern extremity of a shallow coaxial seismogenic domains known as the Tricastin and Marsanne swarms (Thouvenot et al. 2009), we assume that they are co-genetic and relate to the Neogene to Present reactivation of the deep Marsanne Fault imaged on this seismic profile.

As observed in analogue models (Fig. 13), the transpressional reactivation of the high-angle basement-involved Marsanne Fault has resulted in the development of a basement short-cut and neo-formed southwest-verging reverse fault at depth, which connects the basal Triassic décollement

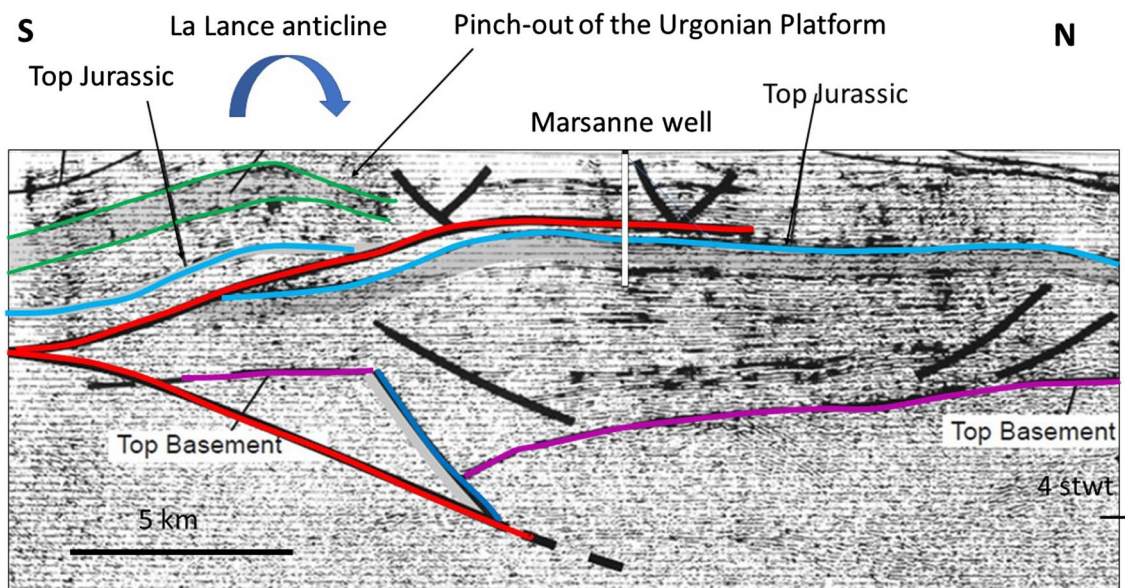


Fig. 12 NS regional seismic profile crossing the western termination of La Lance anticline in the south, and the western subsurface extent of the Fôret de Saou syncline in the north (See location in Fig. 1, after Roure et al. 1992, 1994, modified). Notice the inherited north-dipping Jurassic normal fault and coeval basement indenter propagat-

ing from the Vocontian Trough in the north towards the Valréas horts in the south, and the shallow antithetic north-verging thrust which propagates in the Neocomian series as far north as the Fôret de Saou allochthonous syncline

of the former Vocontian Basin in the north with the Jurassic shales of the former Valréas horst in the south. At shallower levels, the inverted Mesozoic basin acts as a tectonic indenter. This created the development of a triangle zone. The shallow north-verging thrust of the Urgonian platform carbonates of La Lance produced a local antithetic accommodation above the reactivated basement fault.

Worth noting, Le Teil earthquake is associated with the reverse motion of a fault located within the Mesozoic carbonates, and is rooted at shallow depth in more shale horizons (Ritz et al. 2020), near the northwestern extremity of the same Marsanne seismogenic cloud.

3.6 Multistoried decoupling in the Mesozoic sequences of the Diois and Baronnies foothills

An illuminating NS composite seismic profile was initially shot by Esso across the Diois and Baronnies foothills, from the Drôme river in the north at the southern border of the Vercors Massif, almost up to the Ventoux-Lure Massif in the south (Fig. 14; Roure et al. 1986a, b, Roure and Colletta 1992). This composite line was subsequently reprocessed for the FSH, in order to better calibrate the new EW profiles recorded along the Drôme Valley and southern part of the Baronnies.

This profile provides a key to understand how surface geology only documents structures down to the first décollement level. Along the surface trace of the profile, the Brette

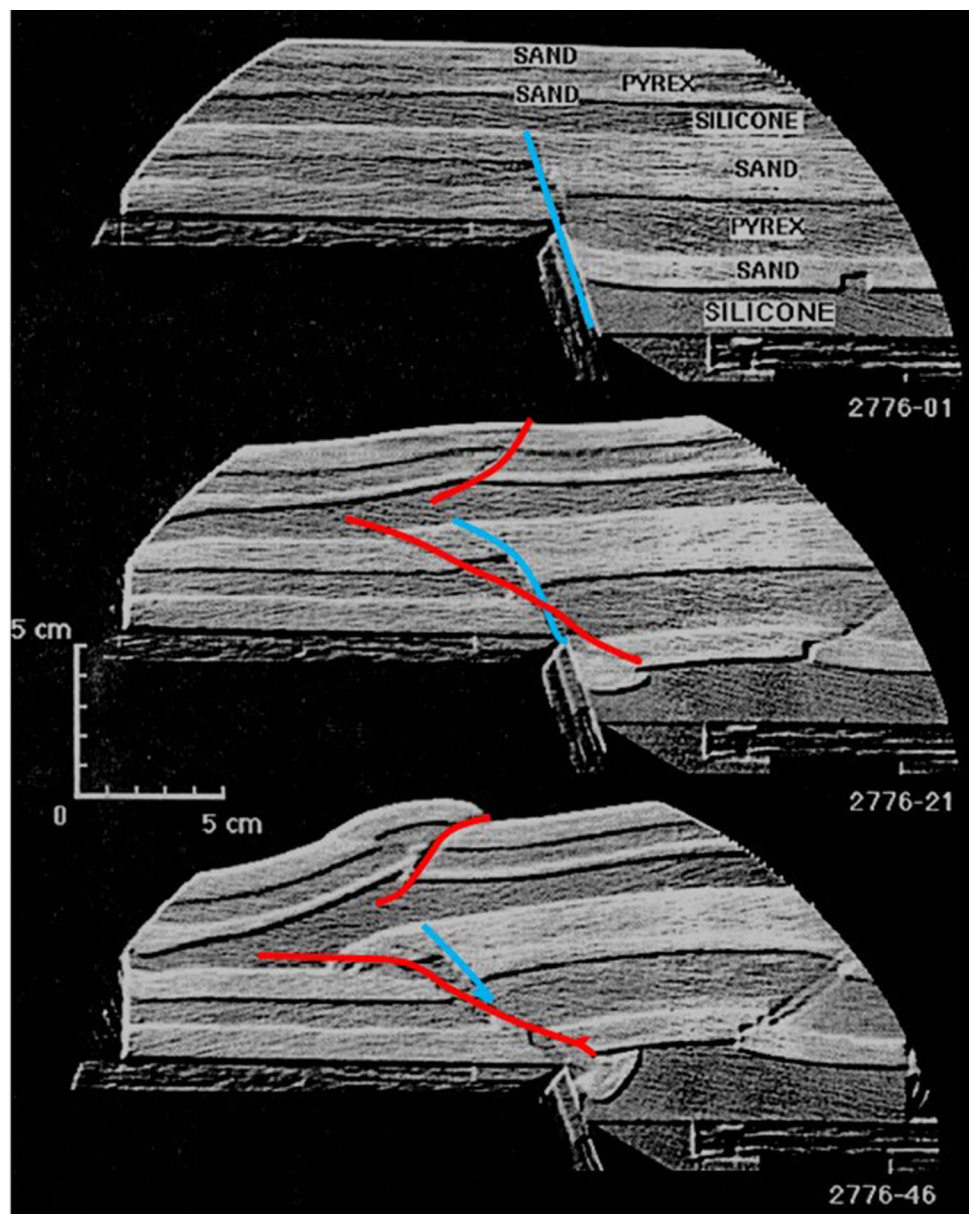
and Barnave anticlines are very tight. The basinal Tithonian carbonates are either vertical or overturned on the northern flank of the Barnave structure.

Below the structure, the seismic profile only documents well preserved normal faults and tilted blocks within the Dogger and Liassic carbonates. These structures are entirely decoupled from both the overlying Tithonian carbonates and underlying Paleozoic substratum. There is no evidence of any compressional structure in these intermediate tectonic units, which are thus totally isolated due to active decoupling along the Oxfordian blackshale and Triassic evaporitic layers.

4 The Châteauneuf-du-Pape diapir and other halokinetic (salt) structures of the SE Basin

Triassic deposits of the SE Basin are locally well exposed in the Crussol Mountain, where they are facing the Valence city on the opposite side of the Rhône River (Riche and Roman 1921; Blanc 1958). They crop out also in the Ardèche margin of the basin, near Largentière, where the basal sandstones host the well known Mississippi Valley Type—MVT—ore deposits (Debrand-Passart et al. 1984, and references therein). Farther east and south, i.e. towards the deeper parts of the paleomargin, Triassic outcrops are restricted to the core of local halokinetic structures such

Fig. 13 Analogue model of basin inversion. Notice the basement short-cut, with a neoformed low-angle thrust cutting through the former high-angle fault, and the antithetic thin-skinned structure in the overlying sedimentary cover (from Roure and Colletta 1996, modified). Final stage of the model is a perfect analogue to La Lance triangle zone



as the Dentelles de Montmirail (also known as the Suzette diapir), and the Propiac and Condorcet diapirs (Fig. 15). The regional reconnaissance surveys made by the FSH provide additional controls on the current burial depth and thickness of Triassic deposits, which constitute a major decoupling horizon between Jurassic carbonates and Permian red beds or Carboniferous coal measures.

The thickness map of assumed Triassic salt and associated depth to the infra-Triassic substratum (Le Pichon et al. 2010; Rangin et al. 2010) is not sufficiently calibrated. The authors did not differentiate the underlying Paleozoic sedimentary horizons and did not interpret the inherited tectonic fabric, which should include the cumulative vertical offsets of basement-involved Permian, and Oligocene normal faults.

4.1 L'Etang Salé and the buried salt dome of Châteauneuf-du-Pape

The occurrence of a salt pond near Courthézon, at the NE corner of the Châteauneuf-du-Pape, has been documented (Fig. 16; Collectif LPO 2010). It was mapped during the eighteenth century, at the time of Louis XV, on the local sheet of the famous Cassini maps, that is still available to the public on the IGN website. Historical records of the Orange principality attest to exploitation of the salt, which remained a privilege of the Prince d'Orange until the early eighteenth century when Louis XIV took power of this formerly Dutch owned region. A tunnel was cored in the early years of the nineteenth century to drain the former marsh and transform it into farm land, but due to the recent collapse of this

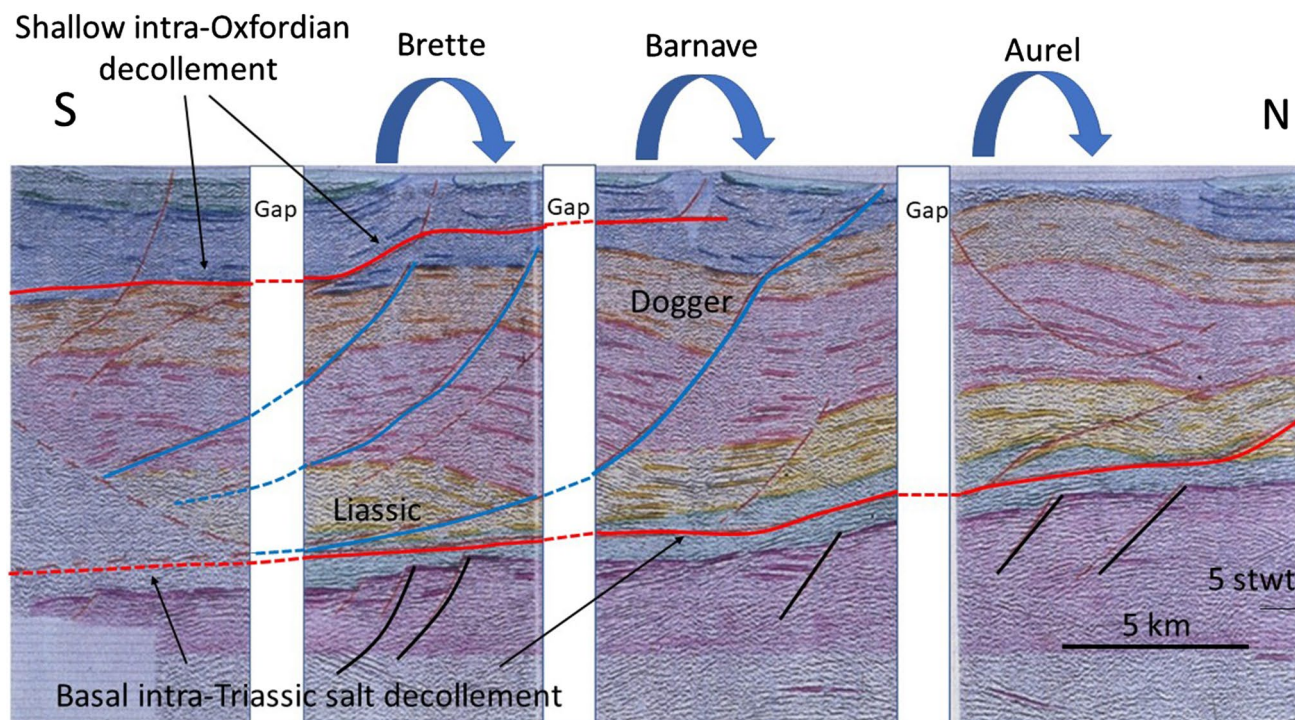


Fig. 14 NS regional seismic profile crossing the Diois and Baronnies (i.e., the Vocontian trough) from the Drôme River in the north to the Angèle Mountain in the south (See location on Fig. 1). Notice the tight or even overturned attitude of the Brette and Barnave anticlines which involve the basal Tithonian carbonates and are detached

within the Oxfordian blackshales. Notice also the normal faults still preserved in the underlying Liassic to Dogger synrift series, which are detached and passively transported above the Triassic evaporites. Deeper reflectors interpreted as Upper Paleozoic series are also imaged at depth, close to the bottom of the profile

man-made outlet, the topographic depression again fills each winter with fresh water as all the salt has now been flushed from the shallow aquifer.

Furthermore, the circular depression hosting the Etang Salé is best interpreted as a collapsed structure associated with the dissolution of the shallow part of the salt dome. Similar structures occur in many salt diapirs around the world. Poorly constrained assumptions consider that a salt dome is still present at a burial depth of 1 km. Accurate hydrologic studies are not available that could define the depth and location of thermo-haline fluid circulations. The high thermal conductivity of the salt is likely to control also local anomalies of the geothermal gradient, which may have some incidence on the productivity of the local vineyards.

Many parts of the Châteauneuf-du-Pape vineyards are covered by rounded cobbles (Fig. 17, top) deposited by the Rhône River during the successive cold and warm periods of the Quaternary (Gabert 1969; Clauzon et al. 2004). The cobble layers occur at various elevations and the highest layers are the oldest deposits. This puzzling distribution of the Quaternary deposits was initially interpreted as reflecting nested alluvial terraces, thus recording the progressive downward erosion and decreasing elevation of the river. Alternatively, as the Châteauneuf-Courthézon area

is obviously strongly impacted by neotectonics, the current topography rather suggests a gentle, progressive oblate doming of the entire structure, parallel to the Nîmes Fault, rather than an abrupt staircase made up of superposed flat terraces.

Our new neotectonic scenario rather suggests the older cobble deposits were at the current level of the Rhône River and through time have been jacked upward as the salt dome rose. Accurate morphometric reconstructions involving high resolution DEM and Lidar acquisitions coupled with new dating methods (optical stimulated luminescence dating using quartz—OSL, thermoluminescence dating—TL, cosmoclides,...) would be required to provide a more robust kinematic model of the salt rise and coeval seformations of shallow Quaternary surfaces.

Despite the lack of seismic profiles in this area, the Châteauneuf-du-Pape is underlain by the NE-trending long active Nîmes Fault (Carbon et al. 1993; Terrier et al. 2008a, b; Terrier 2012; Jomard et al. 2017), which runs from the Costières du Gard in the south, to the Dentelles de Montmirail in the north. The subsurface architecture of the latter is well documented by a seismic profile of the former reconnaissance surveys of FSH (FSH-82SE-4). These well-documented relations will provide an analogue for the subsurface architecture of the Châteauneuf-du-Pape diapir and

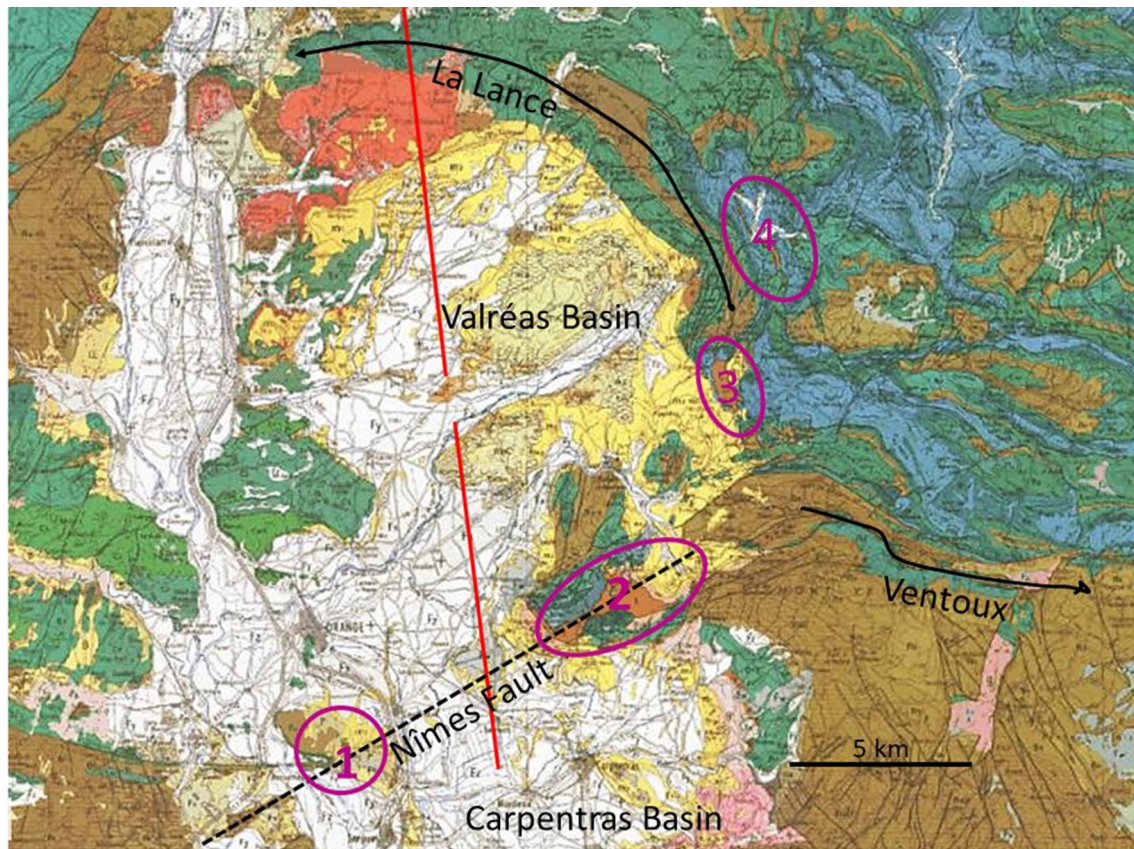


Fig. 15 Regional geological map showing the location of the Châteauneuf-du-Pape diapir, Dentelles de Montmirail and associated Suzette diapir, as well as the Propiac and Condorcet diapirs (extract from the Geological map of France at 1/250.000 scale, BRGM, online on Geoportail)

vertical offset of the underlying Nîmes Fault at basement level (Fig. 17, bottom).

4.2 The Nîmes Fault and the Dentelles de Montmirail structure

The Dentelles de Montmirail provide a direct access to the architecture of a former salt diapir which has been uplifted and laterally transported towards the north during the Neogene inversion of the northern border of Carpentras Basin (Figs. 15, 18, 19).

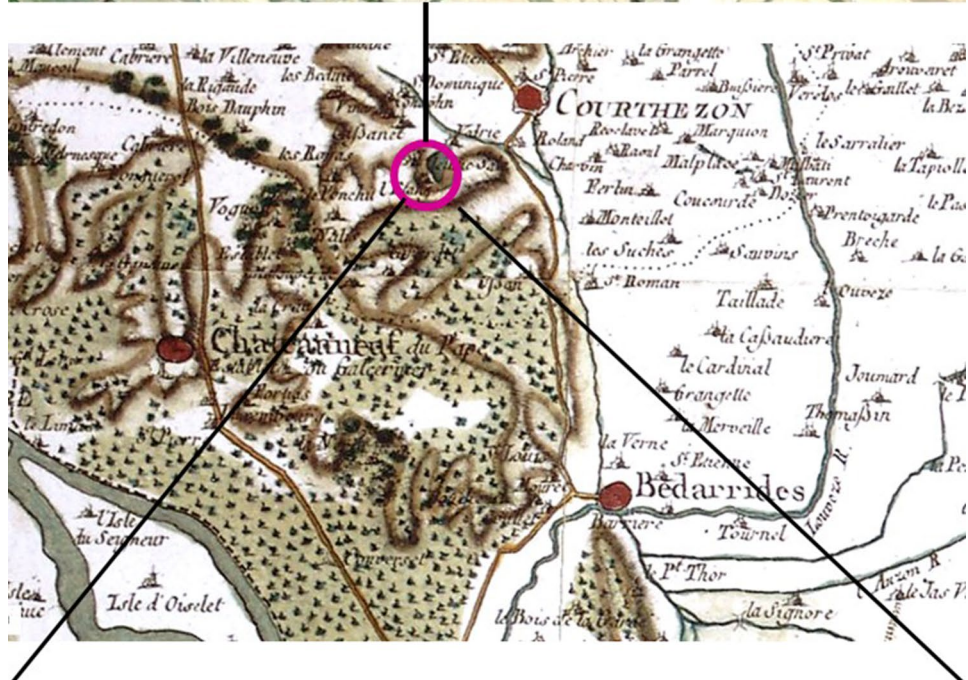
La Salette River, which crosses the Triassic core of the structure from La Fare to Beaumes-de-Venise refers to the occurrence of shallow Triassic salt. Authigenic hydrothermal bipyramidal quartz crystals have also been described from surface Triassic outcrops (Truc, oral communication).

Vertical Tithonian carbonate beds and pinchouts of Lower Cretaceous rimsynclines and minibasins provide evidence of the Mesozoic rise of the salt (Fig. 20). Unconformable Oligocene and Neogene deposits record successive Cenozoic episodes of collapse and compressional inversion of the structure (Casagrande et al. 1989).

The NS seismic profile from the FSH (profile FSH-82SE-4) reconnaissance survey crosses the western buried extremity of the Dentelles trend and displays a major vertical offset of basement along the underlying Nîmes Fault (Fig. 18). This contrast with halokinetic structure that is laterally thrust northward on top of a former Cretaceous rim syncline and extends towards the adjacent Valréas horst. We interpret also low reflectivity horizons interbedded within the Cenozoic infill at the southern border of the Valréas Basin as a former salt glacier or salt tongue that rose laterally from the diapir.

With Dentelles de Montmirail halokinetic structure as an analogue, we can anticipate a vertical offset of basement along the Nîmes Fault associated with the Châteauneuf-du-Pape salt dome. Sand box experiments (Fig. 19) document the complex architecture of salt diapirs at local scale, especially when they have been partially squeezed during subsequent episodes of compression and inversion. Seismic profiles are therefore needed to document the bedding attitude of the Jurassic beds in the footwall of the fault. The profiles could also document the distribution and regional extent of Cretaceous rim synclines or mini-basins as well as

Fig. 16 The Etang Salé, located between Courthézon in the east and Châteauneuf-du-Pape in the west, was already recorded in the XVIII^e century of the Cassini maps (online on Géoportail)



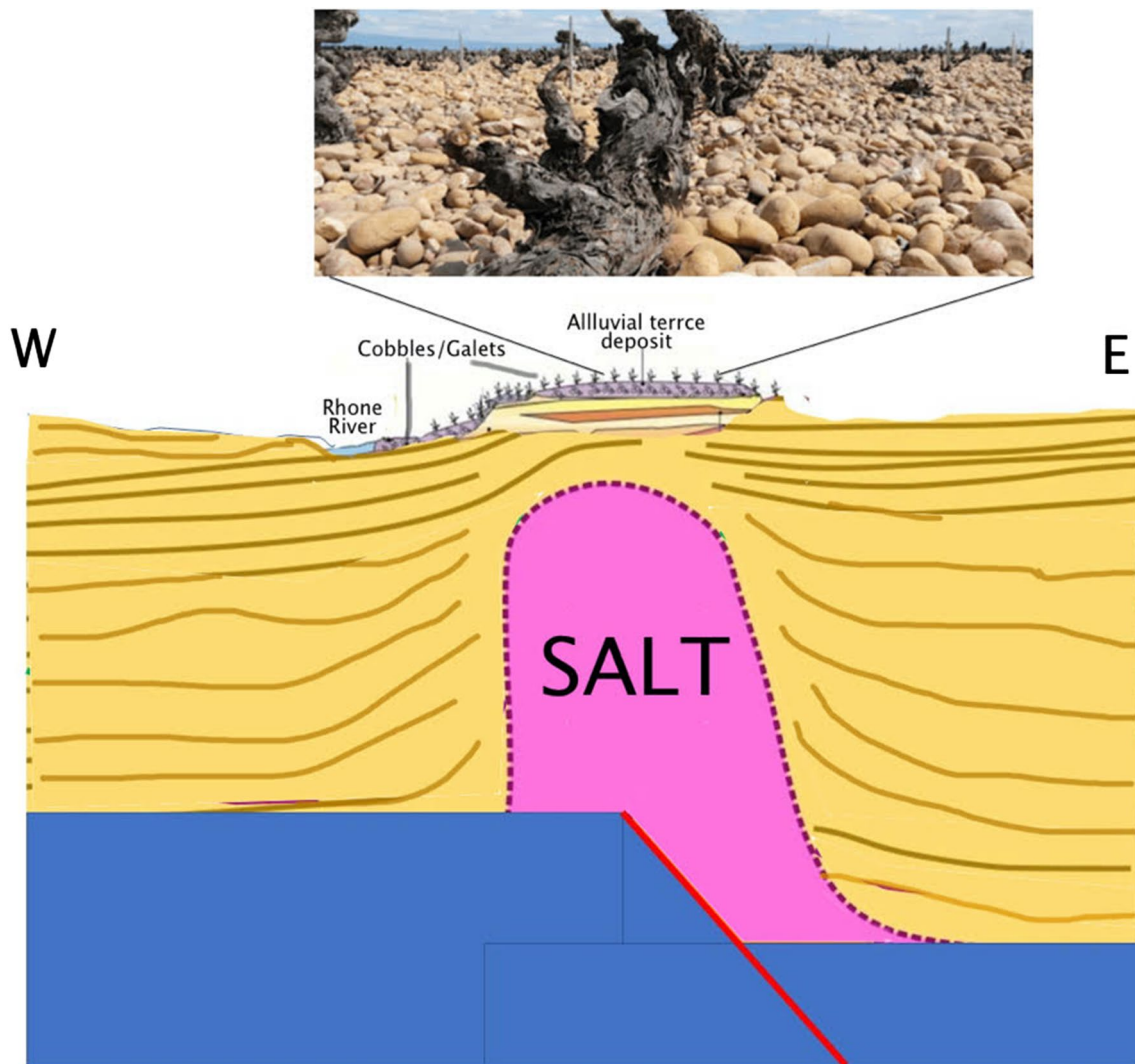


Fig. 17 Top: rounded Pleistocene pebbles at the top of the Châteauneuf-du-Pape diapir, in the Montredon wineyard (photo courtesy Wine-and-Geology Tours). Bottom: cartoon imaging the subsurface

attitude of the Nîmes Fault and Triassic salt dome beneath the Châteauneuf-du-Pape wineyard

the amount of overthrusting and compressional reactivation/inversion of the diapir itself.

4.3 Other salt diapirs of the SE Basin

Surface mapping has also documented other Triassic salt diapirs, associated halokinetic structures, rimsynclines and minibasins in the SE Basin (Célini et al. 2021, and references therein). Examples include the Lagrange area near the Durance Fault, the allochthonous thrust sheets of the Digne area north of the Valensole Plateau, and the Propiac–Condorcet and Dieulefit areas in the western part of the basin (Fig. 15).

Those of Propiac–Condorcet, just north of the Dentelles de Montmirail, along the eastern border of the

Valréas horst, have been properly imaged by the FSH seismic profiles. Colleagues from Ecole des Mines de Paris have identified and dated rapid lateral thickness variations in the Jurassic and Cretaceous rimsynclines associated with salt diapirs (Gracianski de et al. 1987). Yasmine Desmaison also collected numerous bipyramidal hydrothermal quartz crystals redeposited in the Jurassic blackshales near Buis-les-Baronnies, suggesting an early onset of the halokinetic salt motion at regional level (Desmaison et al. 1988).

The FSH profile crossing La Lance anticline indicates the occurrence of another, still buried salt structure at the crest of the basement short-cut indenter, which would suggest also the occurrence of thick Triassic salt deposits in the footwall of the Marsanne Fault.

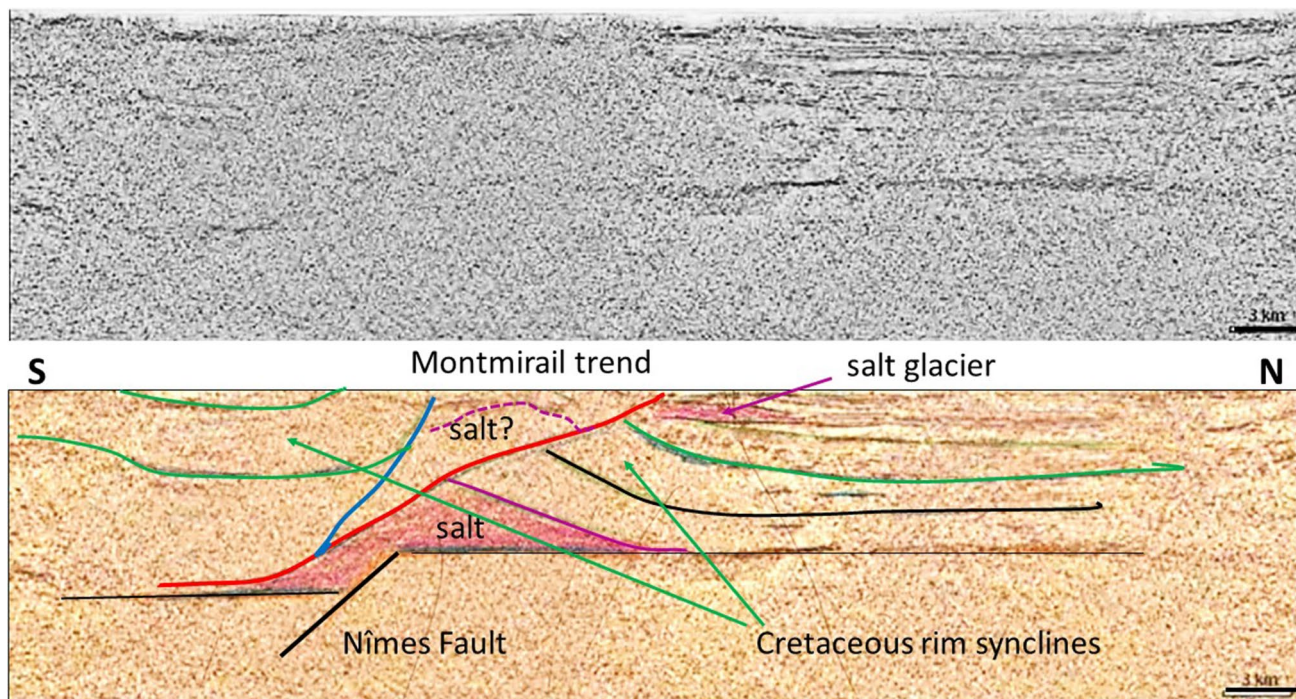


Fig. 18 **a** Uninterpreted NS seismic profile crossing the western termination of the dentelles de Montmirail and associated Triassic diapir of Suzette. **b** Structural interpretation of the same profile, accounting for the positive inversion of the Carpentras Basin and former diapir, above a north-verging low-angle thrust fault. Notice also the normal

vertical offset still preserved in the basement across the Nîmes Fault, the occurrence of Cretaceous rim synclines, and a salt glacier or salt tongue interbedded within the Neogene series of the Valréas Basin in the north

4.4 Saline versus low-salinity brines and evolution of overpressures at basin scale

Despite the fact that no Triassic halokinetic structure has yet been identified along the Ardèche margin, fluid inclusion studies have documented lateral transfers of saline brines from the deep basin towards its margin and the local vertical escape of lower salinity fluids derived from the deeper Permo-Carboniferous aquifers along the high-angle Jurassic faults of the paleomargin (Guilhaumou et al. 1996). They account for the transfer of exotic mineralized fluids associated with Mississippi Valley Type—MVT—ore deposits as well as hydrocarbon accumulations into the shallow Lower Triassic sandstone and Jurassic carbonate reservoirs of the Ardèche margin.

Unfortunately, no basin modelling studies have yet been dedicated to the reconstruction of the overall burial/unroofing history, regional dewatering processes, thermo-haline circulations as well as overpressures and pore-fluid pressure evolution in the vicinity of the major faults of the SE Basin. Such studies would help in understanding seismogenic cycles and hydraulic fracturing episodes.

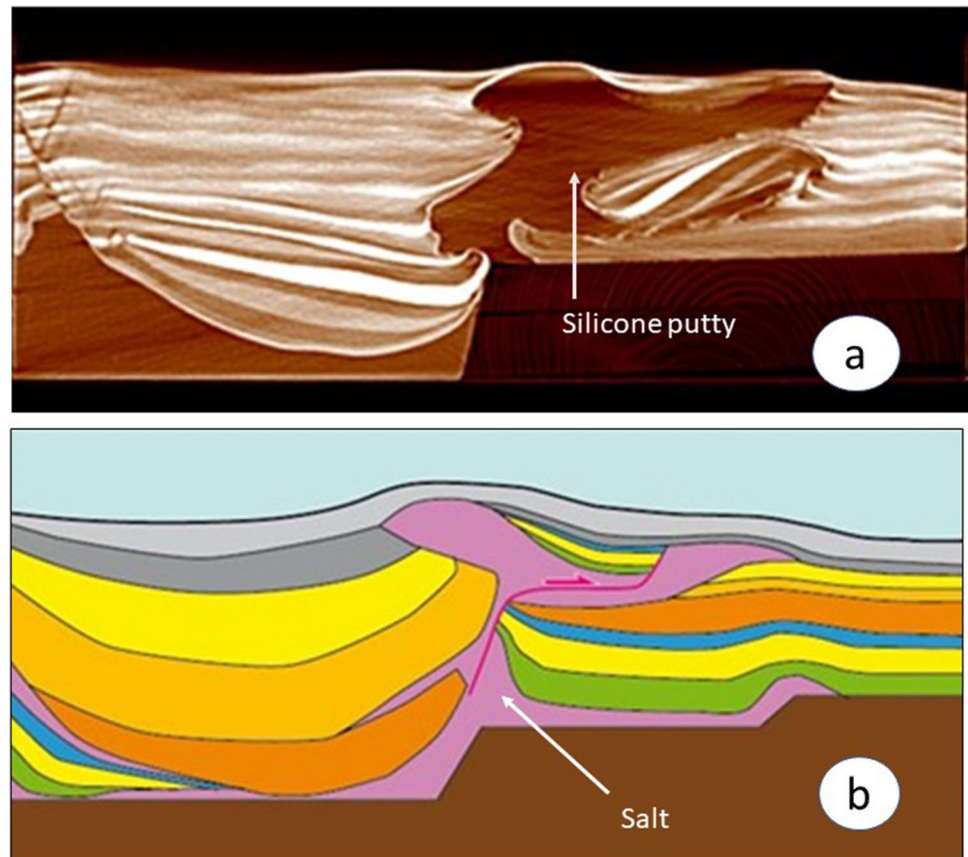
5 Guidelines for the construction of an accurate 4D regional kinematic model and monitoring of the fault system in the SE Basin

In many countries, seismologists do not have access to industry seismic profiles and therefore, they concentrate their work mainly on surficial data, which is obviously insufficient to document the detailed architecture of the fault system, especially in areas where multiple decollement levels account for a complete decoupling between the sedimentary cover and the basement.

In most countries, such profiles remain confidential, belonging to the petroleum exploration companies, but in the few countries where they have been released to the scientific community, they are likely to help integrating the seismological data in a better way.

Ultimately, a national effort should be attempted to compile a regional 3D structural model of the fault systems, identify the domains of brittle versus ductile deformation, which would be helpful to better locate the individual focal mechanisms at depth.

Fig. 19 Sandbox model of an inverted diapir, with final staged imaged by X-ray tomography at the top, and its structural-geological interpretation at the bottom (courtesy Jean-Paul Callot and IFPEN)



5.1 Status of private versus public access to subsurface databases in nearby countries

5.1.1 Algeria

Confidentiality and restricted access to subsurface databases is the policy in Algeria. Sonatrach and the National Agency of Petroleum -ALNAFT- are still reluctant to share their database with geophysicists from the CRAAG and with university colleagues. This is unfortunate as good seismic profiles exist across the Chélif Basin, in the vicinity of the former El-Asnam–Orléansville earthquakes (1954, Mw 6.7; 1980, Mw 7.3; Meghraoui et al. 1988). The imagery of Miocene and Plio-Quaternary sediments and of the entire subsurface fault system would provide constraints on the location of brittle failures and the dating and quantification of recent deformations recorded in the uppermost sediments (Roure et al. 2012).

5.1.2 Albania

Bettim Muço and Anastasia Kiratzi could update the national Albanian earthquake catalogue as part of the Albaisis project. This would be supported by the Science for Peace program from NATO but they choose not to use

seismic data from the Albanian Petroleum Institute of Petroleum and Albpetrol which is now part of the National Agency for Energy and Petroleum.

Most earthquakes in the Albanian foreland are located along the Vlora-Elbasan lineament. Seismic imagery suggests these earthquakes relate to a major lateral ramp between the inverted Ionian Basin in the south and the Periadriatic Depression in the north (Muço 1994, 1998). The ongoing compressional deformations south of this lineament are aseismic. Allochthonous Ionian units are translated westward along the ductile Triassic evaporitic and salt layers. Overpressured Cenozoic shale horizons accommodate the thrust motions in the Periadriatic Depression. It is only along the Vlora-El Basan lineament—the subsurface ramp joining these two décollement surfaces—that brittle failures occur in places where the thrust trajectory is crossing Mesozoic carbonate units.

GPS data are available, both in the hinterland and the foreland (Speranza et al. 1992; Jouanne et al. 2012; Guzman et al. 2013). In the latter, the data record a surficial rotation of allochthonous Ionian units in the vicinity of the Vlora-El Basan ramp. These data are in agreement with the overall decoupling between the overriding units and their autochthonous footwall.

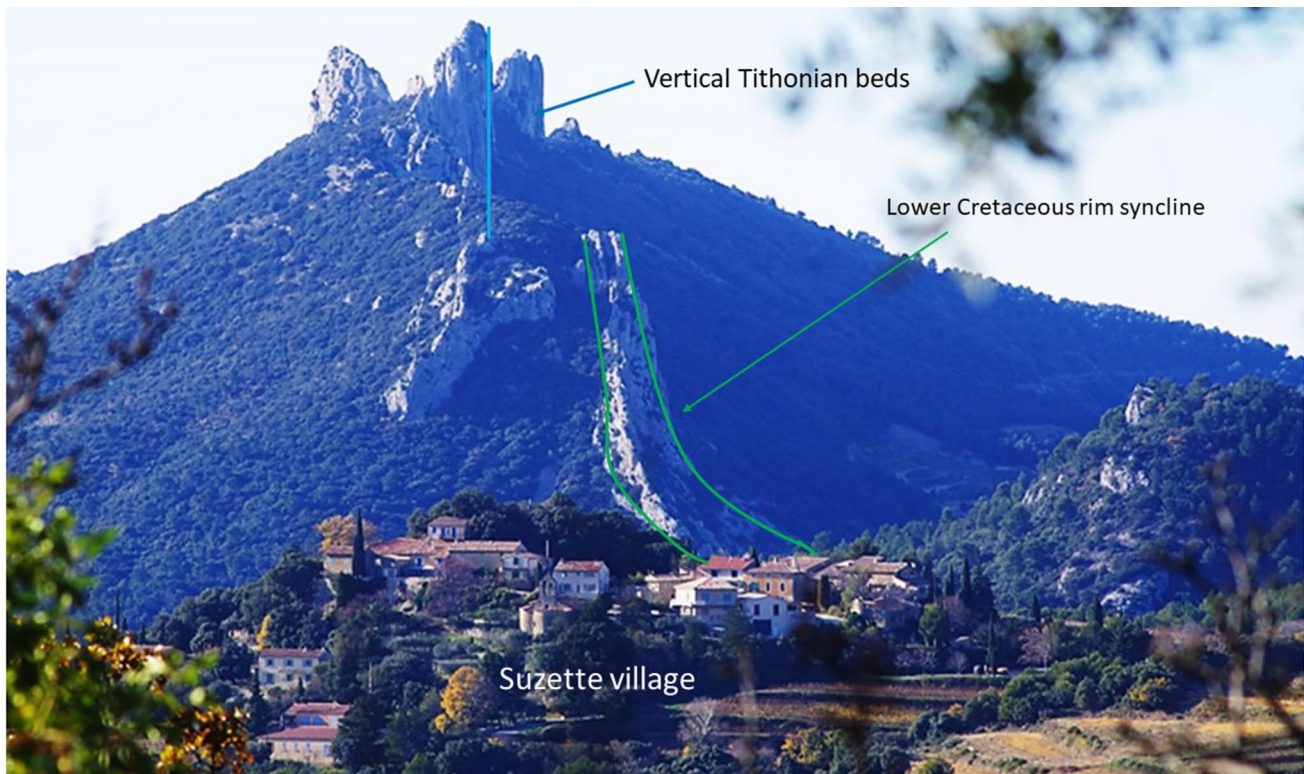


Fig. 20 Panoramic view facing towards the west. Notice the Suzette village, located in the Triassic series exposed in the core of the diapir, and in the background, the vertical Tithonian beds and the fan-shaped attitude of Lower Cretaceous in the adjacent minibasin

Long-term seismologic records compiled by Bettim Muço record a seasonality for earthquakes. Most earthquakes seem to happen during the rainy season, when the water table is rising in subsurface aquifers and karst cavities become filled with water (Muço 1995).

The seismic database provided by the Albanian Petroleum Institute and National Agency allowed Laurie Barrier and Nadège Villasi to construct a 3D structural model of thrust surfaces and then to apply thermal, petroleum and fluid flow modelling techniques on selected 2D lines (Vilasi et al. 2009; Roure et al. 2010a, b, 2013). These models constrain both kinematic and pore-fluid pressure parameters, and allow for a full 4D Pressure and Temperature predictive model for the Ionian Basin.

5.1.3 Italy

At the initiative of Piero Casero and the Geological Society of Italy, the ministry of economy—DGRME—and ENI have released a set of location maps, 2D onshore and offshore seismic profiles as well as compilations of exploration well data (www.videpi.com). These data are available on line for the public on the Videpi website. Although the quality and processing of the on-line profiles are not always as good as the original data, they constitute a valuable subsurface

data-set for any scientist who is interested in sedimentary basins in Italy.

Owing to his connections to the petroleum industry, Claudio Turrini was able to compile a 3D comprehensive crustal-scale structural model of the Po Basin, using both 2D and 3D seismic campaigns. These were augmented by deep seismic profiles recorded by CROP. Although the resolution is not as good in the infra-Triassic substratum, his model provides controls on the subsurface trajectory of the North Apennines thrust system within the Mesozoic and Cenozoic series. Collaboration with INVG, provided data constraining the location of major seismic events as part of his 3D model (Turrini et al. 2014, 2015). As a result, it becomes obvious that most seismicity and brittle deformation occur at places where the thrust ramps cross the Mesozoic carbonate units, as well as at deeper levels where high-angle faults in the basement are locally reactivated. The intervening Triassic evaporitic layers accommodate ductile horizontal transfer of the tectonic wedge during its progression towards the foreland, without seismicity along the basal decollement.

Recent 3D tomographic models based on long-term passive seismic recordings provide a first order model of the seismic velocity at crustal scale beneath the South Alpine and North Apenninic realms and the adjacent Po Plain (Potin 2016; Lu et al. 2020; Nouibat et al. 2021). As indicated

above, they demonstrate the overall thinning of the crust beneath the Rhône Valley in the SE Basin (Lu et al. 2020; Nouibat et al. 2021). The resolution is better beneath the Po Plain, and consequently these tomographic models can provide control of the structure of low-velocity siliciclastics (Miocene and Plio-Quaternary sediments) versus underlying high-velocity Mesozoic carbonates (Potin 2016).

5.2 Tentative plans to image regional fault systems, subsurface fault trajectories, and to accurately date and quantify recent deformations in the SE Basin

5.2.1 Petroleum and nuclear backgrounds of the SE Basin

In France, industry seismic profiles are released to the public after 10 years. Data from onshore wells are made available soon after drilling while data from offshore wells remain confidential forever. These subsurface data are now managed by the French geological Survey—BRGM—which sells access to old seismic profiles.

Because exploration for hydrocarbons is currently forbidden in France, petroleum companies will no longer record seismic profiles in the near future in the SE Basin or anywhere else. All applications for blocks likely to host shale gas have been canceled due to the recent ban of hydraulic fracturing.

As the French government is planning to rejuvenate our nuclear industry and build new nuclear plants, it becomes urgent to improve our understanding of the overall fault architecture and related seismic hazards in the SE Basin (Fig. 2).

It is vital for the scientific community to propose research programs that include both regional and local geophysical acquisitions in order to ascertain the local risk from earthquakes. This must include defining the location and nature of subsurface faults and their cyclicity and potential magnitude. The cost of such a research program is small compared to the costs associated with delays of construction of a new EPR such as at Flamanville.

5.2.2 Needs for at least two regional deep seismic reflection profiles at regional scale

High-angle faults and Carboniferous thrusts have not yet been properly imaged by conventional industry profiles in the SE Basin. This lack of imagery stems from the great thickness of Mesozoic sediments deposited east of the Cévennes and Nîmes faults. We know however from the former Ecors seismic reflection profiles across the Aquitaine foreland of the Pyrenees and the Paris Basin that they would provide the requisite resolution to define the overall attitude of the Moho and lower crust associated with the Tethyan and

Oligocene crustal thinning, location and nature of Permian normal faults and Carboniferous thrust faults. The Permian and Carboniferous structures likely control the placement of Mesozoic and Oligocene extensional structures and their Pyrenean and Alpine reactivations.

Paleozoic and Mesozoic structures are dominantly EW-trending Permian basement faults and NE-trending Mesozoic and Oligocene normal faults. These two contrasting structural orientations require shooting at least two orthogonal regional seismic profiles to understand both the deep architecture of the SE Basin and the younger basement faults reactivated during episodes of post-Cretaceous compressions.

5.2.3 The need for a robust regional network of conventional seismic profiles and more localized high-resolution seismic profiles

We cannot rely on surface geology and geological maps edited by the BRGM to predict the location and trajectory of the faults in the subsurface. This is demonstrated by noting the blind Jurassic normal faults lying below the post-rift unconformity west of the Ardèche Fault, and also by the listric attitude of the Corconne and Cévennes faults on Total and Elf-Aquitaine seismic profiles that occur within the sedimentary cover or in the infra-Triassic basement.

Therefore, to understand the earthquake potential, it is necessary to record a network of conventional seismic reflection profiles across the Mesozoic and Oligocene fault systems where this information currently does not exist.

Geophysical surveys based only on potential field data such as magneto-telluric, electric prospecting, gravimetry, and magnetic surveys, generally do not have a sufficient resolution to document small-scale deformation in the sedimentary strata. Therefore, higher resolution seismic reflection profiles need to be designed for areas where potential faults are covered by thick Cenozoic strata. After a major sea level drop and coeval erosion during the Messinian, thick Plio-Quaternary strata have progressively filled the paleocanyons of the Rhone and adjacent rivers (Gargani 2004; Roure et al. 2007; Mocochain et al. 2009; Bailly et al. 2018; Capella et al. 2018). These recent sedimentary records may display recent faulting. Properly locating places to dig shallow trenches would enable dating recurrence intervals and estimating the magnitude of recent earthquakes.

5.2.4 Needs for moderate to long-term GPS monitoring across the various tectonic blocks and around the Châteauneuf-du-Pape diapir

The accuracy of GPS is sufficient to measure the relative vertical and horizontal offsets between two points, provided the recording time is long enough to display cumulative

displacements, which must indeed exceed the value of the error bars (Calais et al. 2002). Although local velocities may be very low in the SE Basin, in the range of 1 mm/year, preliminary results have been already obtained locally (Masson et al. 2019; Mathey et al. 2020).

The Châteauneuf-du-Pape dome lends itself to such a GPS study because we do not know at this stage what is the velocity of its tectonic uplift, nor the amount of coeval transcurrent motion likely to still operate along the underlying Nîmes Fault.

Villéger and Andrieux (1987) have also demonstrated the relative rigidity of the Urganian Platform within the North Provençal tectonic block, which extends from the Ventoux-Lure trend in the North, the Luberon in the south, and the Durance Fault in the east (Hippolyte et al. 1991; Ford and Stahel, 1995; Molliex et al. 2011; Fig. 20). GPS measurements have been already initiated between selected points located within this regional tectonic block, but also farther east in the more stable Valensole Plateau. Because of the rather small velocities expected in the area, longer term recording will be required to quantify both the relative vertical and horizontal motion of the inverted block with respect to Valensole horst. It also would quantify the amount of strike-slip motion operating along the Durance Fault between these two domains.

5.2.5 The need for additional longer term passive seismic monitoring in the vicinity of the Châteauneuf-du-Pape diapir

Although vibroseis could be used as an alternative to explosive sources, it may prove to be difficult to shoot seismic profiles across the Châteauneuf-du-Pape vineyards. Another technique might be more suitable. Mixing passive seismic and gravity modelling have been used with success by Enterprise in Greece where seismic surveying is not allowed. Fortunately, ongoing natural seismicity is sufficient in Greece to constitute an excellent source, allowing to build a 3D velocity model of the subsurface during a several month-long recording period. Salt and carbonate rocks each have the same seismic velocity profile, in the range of 5 km/s. Because salt is less dense than carbonate, Enterprise was able to discriminate between a salt dome and carbonate mass in compiling a 3D structural model (Durham 2003; Kapotas et al. 2003; Martakis et al. 2006). The resolution was excellent, as they succeeded in drilling a well down to their carbonate target.

5.2.6 Further opportunities to date radiometrically the cements associated with the successive slip events of individual faults

Radiometric dating techniques using Uranium–Lead isotopes are now available routinely in specialized labs for

carbonate cements, even in France. As many polyphased high-angle fault surfaces display various sets of vertical and horizontal slicken-sides associated with coeval cements, it is possible to date different episodes of slip in order to date successive paleo-stress episodes.

5.2.7 Further opportunities to address fluid flow and pore-fluid pressure reconstructions along representative 2D cross-sections and/or 3D blocks

In addition to all the structural models within the Mesozoic and Cenozoic stata, 2D or 3D fluid flow modelling, pore-fluid pressure reconstructions, as well as simulation of thermo-haline fluid circulations, are needed to fully understand the long-term behaviour of faults. This includes fluid pressures and the generation of overpressures which impact the rheology of shale horizons and their coupling/decoupling with interbedded carbonates at basin-scale.

6 Conclusions

The recent uplift and doming of Châteauneuf-du-Pape vineyards, the Quaternary reverse low-angle fault and recent collapse of the underlying salt dome at the Etang Salé near Courthézon, and the destruction of La Lone aqueduct in Roman time, collectively indicate ongoing tectonic activity operating along the Nîmes Fault. This fault is located in the vicinity of the Marcoule nuclear fuel processing and storage site.

These relations and the occurrence of Le Teil earthquake of November 11, 2019, demonstrate a need to investigate the subsurface architecture and recent kinematics of the Cévennes and Marsanne faults in the vicinity of the Cruas and Tricastin nuclear plants.

With a government mandate to expand the capabilities of nuclear power, data relevant to the earthquake potential of the SE Basin are needed, in the event this area is selected for future construction of nuclear plants and EPRs.

In the Rhône Valley near existing nuclear facilities, where little reprocessing of existing FSH regional profiles had occurred to date, new, ongoing seismic acquisitions have been initiated by EDF. In the vicinity of ITER facilities and Durance Fault, CEA and CEREGE reprocessed former seismic profiles that were recorded by Total in the former Manosque-Valensole exploration block. INRS also recorded in the same area a very short, too short-term tomographic survey based on passive seismicity.

At the scale of the SE basin, however, we are still missing robust 3D architectural models describing the subsurface location and trajectory of faults, both in the sedimentary cover and in the pre-Triassic substratum. Such models are

needed to characterize the risk of seismic hazards in the whole area.

The priority for the French authorities and research founding agencies, EDF and CEA and other nuclear lobbies, should be the acquisition of geophysical data to evaluate the potential location and magnitude of future earthquakes. These studies are needed to inform where future nuclear facilities could be safely located.

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