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Evidence for an intra-Oligocene compressive event in the Marseille-Aubagne basins (SE France)

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ABSTRACT

An Oligocene tectonic event has been suspected as the origin of thrusts and folds in several Oligocene troughs and basins of Provence, including the Marseille-Aubagne basins. Deformations are generally assumed to be to a post Oligocene extensional event. The Marseille-Aubagne basins are geographically and stratigraphically separated into three basins (Jarret, Prado and Aubagne) with each of them exhibiting their own sedimentary succession. However, each of the successions includes two main units:
- The lower unit which includes several formations attributed to the Rupelian age. All of these sediments are strongly or slightly deformed depending on their location with respect to the main faults.
- The upper unit which includes formations of mainly Chattian age. They are undeformed or slightly deformed.

Geological sections across the southern Prado basin show a succession of anticlines and synclines. Additionally the thrusting of the Carpiagne massif over the Prado basin has been evidenced since 1952. These deformations are here related to a compressional event

According to palaeontological data, the latest deformed strata are ascribed to the Late Rupelian, whereas the earliest undeformed strata are ascribed to the Latest Rupelian. This is in accordance with age determinations on detrital zircons extracted from the latest deformed sandstone, and from the youngest age of detrital zircons from the undeformed sandstone. Thus, the stratigraphic limit between the deformed and undeformed formations should be set around the Rupelian / Chattian limit (28.1 Ma) according to the latest chronostratigraphic chart. Finally, we discuss correlations with similar events occurring around the Mediterranean area.

Key words: compressive event, Marseille-Aubagne basins, Oligocene, Western rift

Evidencias de un evento compresivo intra-Oligoceno en las cuencas Marsella-Aubagne (SE Francia)

RESUMEN

Las deformaciones de los sedimentos oligocenos relacionadas con las fases de extensión en las cuencas de Marsella-Aubagne, se han puesto en evidencia desde 1990. Sin embargo, en varias ocasiones y por diferentes autores, ya se habían mencionado deformaciones en régimen de compresión en estas *tierras, sin una conclusión real. Nuestras investigaciones para la actualización de la 3ª edición del mapa geológico de Marsella-Aubagne, nos permite conocer la estructura de las cuencas y mostrar que sólo las formaciones Rupelienses habían sufrido deformaciones en régimen compresivo. Las formaciones más jóvenes (principalmente chattienses) poco deformadas, reposan en discordancia sobre las formaciones rupelienses. Por tanto, existe una gran discordancia tectónica entre los dos grupos de formaciones. Las deformaciones compresivas están relacionadas con dos eventos distintos (TC-1 y TC-2) desde el punto de vista de su geometría, pero sub-contemporáneos. En efecto, los pliegues TC-2 deformaron los ejes de los pliegues TC-1 y son forzosamente posteriores a estos últimos. Por lo tanto, las dataciones cronoestratigráficas y radiométricas muestran que estos eventos están situados en una ventana temporal próxima al límite entre el Rupeliense/Chatiense (28.1 Ma). Una tercera fase tectónica (TC-3) ha producido pliegues en el Chatiense y Mioceno inferior pero su relación con otro régimen compresivo no ha sido establecido.*

Palabras clave: cuencas sedimentarias Marsella-Aubagne, Oligoceno, compresión, rift occidental europeo

VERSIÓN ABREVIADA EN CASTELLANO

Introducción y metodología

Las cuencas del Oligoceno de Marsella-Aubagne se corresponden con las depresiones alineadas de este a oeste y bordeadas por macizos sucesores de la cadena pirenaica-provenzal erigida en el Eoceno. Las diferentes fases tectónicas de extensión de la cuenca oligocena de Marsella-Aubagne ha sido objeto de investigaciones anteriores. La principal deformación compresiva admitida por estos autores han estado atribuidas generalmente a un período post-Oligoceno. Por contra, la existencia de una deformación compresiva intra-Oligoceno en las cuencas de Marsella-Aubagne ha sido objeto de controversia durante décadas, hasta que fue admitida en las cuencas oligocenas de Var y también en la cuenca St Pierre-les-Martigues, donde los cabalgamientos intra-Rupelienses se han puesto en evidencia. En el perímetro de la cuenca de Marsella-Aubagne los juicios son muy compartidos sobre la existencia de esta fase de deformación compresiva intra-Oligoceno. En 1978 Weydert y Nury levantan el corte en el segundo emisario que atraviesa, de norte a sur, la parte occidental de la cuenca de Huveaune que ahora se llama la cuenca del Prado. Sin embargo, en su tesis, Nury no contempla una fase de compresión generalizada intra-Oligoceno. Pantaine pone en evidencia las estructuras plegadas en la parte sur de la bahía de Marsella que es paralela con las del corte del segundo emisario. Finalmente Philip evoca las deformaciones en los terrenos oligocenos de las cuenas de Marsella, sin entrar en mayor precisión. En última instancia, esta fase de compresión intra-Oligoceno evocada a veces y luego olvidada, merece una investigación específica, realizada como parte de la 3ª edición del mapa geológico de Marsella-Aubagne, a partir de los datos de superficie. Este es el propósito de esta nota.

Resultados y discusiones

El número de cuencas es tres: cuenca Jarret en el norte, el Prado en el suroeste y de Aubagne al este (Fig. 1). Han sido rellenadas por acumulaciones detríticas potentes (hasta 1000 m), pertenecientes al Oligoceno y recubiertas de brechas, de arcillas, areniscas y travertinos de edad comprendida entre el Mioceno y el presente. Las nuevas investigaciones geológicas han mostrado que la mayor parte de las formaciones del Rupeliense presentan fuertes pendientes (de 30° a 90°), mientras que las formaciones del Chatiense presentan pendientes bajas (0° a 20°). La Figura 1 muestra algunos afloramientos característicos. Se observa que las capas (So) tienen pendientes entre 30° y 90° en las cuencas del Prado y de Aubagne así como en Maurins, en la parte oriental de la cuenca de Jarret. En algunos lugares se observan pliegues métricos. Por contra, en la cuenca de Jarret las capas calcáreas de Estaque y bajo Bédoule, así como las arcillas de Joliette muestran pendientes regulares y bajas de 0° a 20°. Las deformaciones también se observaron a escala de afloramiento en la misma cuenca de Jarret y especialmente en el valle de Maurins. La figura 2b es una interpretación del corte del emisario II. En el corte de la Barasse levantado por G. Denizot se observó el cabalgamiento de las formaciones secundarias del macizo de Carpiagne sobre las del Oligoceno (Fig. 2c). En la cuenca de Aubagne, el corte de la Gastaude (Fig. 2d) muestra el contacto de falla entre las areniscas de la formación de Gastaude (Rupeliense p.p.) y las areniscas y pudingas de la formación de la Royantge (Chatiense p.p.). A la escala de los cortes transversales a las cuencas (Fig. 4) se observan pliegues kilométricos en las formaciones atribuidas al Rupeliense y en las capas subhorizontales atribuidas al Chatiense y

especialmente en las cuencas de Jarret y de Aubagne. Los diagramas de Wulff muestran claramente las diferencias tectónicas entre las pendientes de los planos estratigráficos del Rupeliense (Fig. 4a y 4b) y los del Chatiense (Fig. 4c). En el mar, en la parte sur de la bahía de Marsella (al sur de las islas de Frioul), Pantaine observó grandes estructuras anticlinales y sinclinales en los perfiles sísmicos de las misiones Marsolig. El perfil interpretado en la figura 5 muestra pliegues a gran escala en formaciones posteriores al substrato cretácico de las islas de Frioul. Pantaine pone en equivalencias las formaciones superiores con las formaciones de la cuenca del Prado y en especial con las descritas por Weydert y Nury en el corte del emisario II. De este modo, tres tipos de deformaciones se han demostrado, fuera de las tectónicas en distensión señaladas por Hippolyte y sus asociados. Estas son: TC1 (grandes pliegues SW-NE), TC2 (deformación pliegues TC1 en pliegues de eje NS) y TC3 (deformación que está en el origen de las estructuras sinclinales que Pantaine, ha puesto en evidencia en la parte norte de la bahía de Marsella y que afecta a las formaciones del Mioceno inferior). Sólo las deformaciones TC1 y TC2 que son de interés aquí, han sido objeto de investigaciones en relación con la edad de su formación. Se seleccionaron dos muestras para determinar las edades de sus circones heredados: una tomada de la formación de arenisca de Gastaude (V240b) y la otra tomada de la formación de arenisca de la Bonne Jeanne (BJ1). Estas dos muestras situadas a menos de 1 km el uno del otro (Fig. 2d) son, respectivamente, los testigos de las formaciones situadas por debajo y por encima de la discordancia tectónica. Estas dos formaciones están separadas por una falla subvertical. La edad de la muestra V240b calculada sobre los circones más *modernos es de 28.74 ± 0.54 Ma (Fig. 6), mientras que la edad calculada sobre los dos circones concordantes de la muestra BJ1 es 27.40 ± 0.51 Ma (Fig.7). Las pudingas de la Gastaude pueden ser más o menos contemporáneas de los primeros depósitos no deformados de la formación de San André/ Saint Henri. En términos generales, la discordancia intra-Oligoceno pone de relieve que las cuencas de Marsella-Aubagne no parecen haber afectado a las cuencas del Oligoceno situadas al oeste de la falla de la Durance. Por contra, al este de esta falla, esta discordancia ha sido señalada por varios autores (Fig. 8). El primero que ha hablado de una "fase tectónica oligocena de origen profundo" ha sido Cecile Cornet. Para ella esta fase tectónica es intra-Oligoceno. Nosotros creemos que el origen de estas deformaciones intra-Oligoceno Marsella Aubagne se debe buscar en el funcionamiento del margen activo del Oligoceno del Tetis (Fig. 9). De hecho, las cuencas de Provenza se encuentran en la prolongación septentrional de la cuenca de arco posterior del margen Ibérico. Sin embargo, los modelos actuales de este tipo, entre ellos Indonesia, muestran que los arcos volcánicos se desplazan constantemente mediante la apertura de las cuencas de arco posterior si divergen, y al contrario, deformando las cuencas de arco posterior, si convergen. Nosotros planteamos la hipótesis de que los movimientos convergentes han tenido lugar al nivel del arco Corso-Sardo en el momento del "rifting" que ha precedido la apertura del Mediterráneo occidental.*

Introduction

The Marseille-Aubagne basins are located in lowlands inside the Pyrenean-Provencal belt. These lowlands are limited by the Nerthe and Etoile massifs to the north, the Ste-Baume massif to the east and the Calanques massif to the south (Fig. 1). To the west, the basin is limited by the bay of Marseille. Three separate basins have been distinguished: the Jarret basin to the north, the Prado basin to the south west and the Aubagne basin to the east.

Nury and Reynaud (1986), Nury (1988) and Hippolyte *et al.* (1990, 1991 and 1993) evidenced several tectonic stages, all of them characterized by an extensive regime. Their main compressive event is assumed to have taken place at the post Oligocene time.

Nevertheless, the presence of an intra Oligocene compressive event in the Marseille-Aubagne basins was a matter of debate for a long time. Cornet 1964, 1965 and Touraine 1976 admitted such an event in the Var, whilst Nury (1972) and Guieu (1973) described intra-Rupelian thrusts in the St Pierre de Martigues basin which is situated within the Nerthe chain, west of Marseille. But new research (Andreani *et al.,* 2010) on the Nerthe chain did not find evidence for such an event. Within the Marseille-Aubagne area, there are dissenting opinions on the presence of such a compressive event. By 1977, Guieu delineated a shrinking of the Oligocene formations related to a moving to the north of the Carpiagne massif by the Early Chattian. Although these folded structures were uncomfortably covered by Late Chattian formations, he ascribed these deformations to a post Pliocene event.

In 1978, Weydert and Nury (1978) performed a geological cross-section within the Emissaire II gallery which went through the Huveaune basin, today known as the Prado basin, (Nury *et al.,* 2013). They measured a lot of dips of more than 30° both northwards and southwards. Therefore, they deciphered several open anticlines and synclines. Then, in 1980, Nury showed that the Oligocene plated limestone is almost vertical and represents a syncline in the Canal de Provence gallery. By considering a late Oligocene age for the breccias unconformably overlying this limestone, she suggested a Late Stampian (i.e. Late Rupelian) tectonic event. But she did not describe a global stampian tectonic event in her thesis (Nury, 1988).

This question was reopened by Pantaine (2010) when he studied the seismic profiles of the Marsolig campain in the bay of Marseille. He evidenced that the folding in the southern part of the Marseille bay, is consistent with the observations of Weydert and Nury (1978). However, his conclusions were rejected by the jury of his Master's thesis. Then, Philip (2013) reported some deformation in the Oligocene basin but without any information on their dating. This question still remains open to debate.

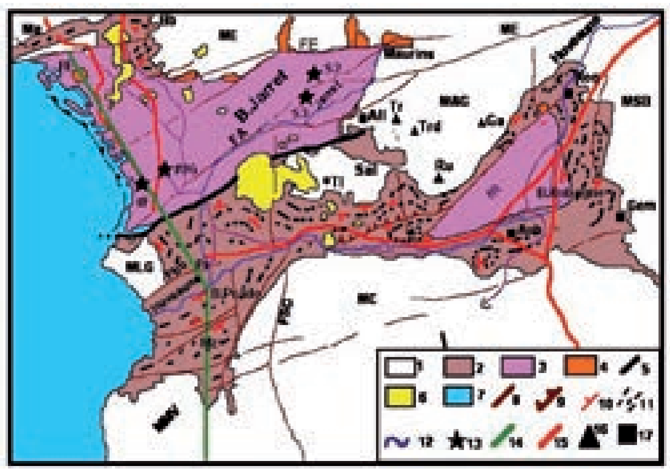

Figure 1. Structural scheme of the Oligocene formations and Pleistocene travertines in the Marseille-Aubagne basins. Legend: 1- Mesozoic basement, 2- Early Oligocene (Rupelian), 3- Late Oligocene (Chattian), 4-Etoile breccias, 5- southern limit of the Jarret basin, 6- Pleistocene Travertines, 7- Mediterranean sea, 8-fault, 9- thrust, 10- S0 plane,11- S0 trends, 12- folds, 13- boreholes, 14- "Emissaire" I (north) and II (south), 15- highways, 16- main peaks, 17- cities. Basins: B.Jarret: Jarret basin, B.Prado: Prado basin, B. Aubagne: Aubagne basin. Massifs : ME- l'Etoile massif, MAG- Allauch–Garlaban massif, MSB- Ste Baume massif, MC- Calanques massif, MMV- Marseilleveyre massif, MLG- la Garde massif, Sites : Ma-Marinier, Bb-basse Bedoule, Mz-Mazargues, Pr-Prado, Tl-Trois Lucs, Sal- Salette, fR-La Royante. Peaks (triangles): Tr-Tête rouge peak, Trd:-   ,Ru : Ruissatel peak, Ga: Garlaban peak. Cities (squares): All-Allauch, Roq-Roquevaire, Gem-Gemenos, Aub: Aubagne. Boreholes (stars): fF: Fournier borehole, fUG : Usine à Gaz borehole, S2 and S3: Plan de Cuques boreholes. Faults: FE1: Estaque fault, FE2 : Etoile fault, Fbb: Huveaune fault, FA: Amandier fault, FSC: Sainte Croix fault. Circled numbers (3A, 3B, 3C, 3d): location of cross sections a,b,c,d in Figure 3.

Figura 1*. Esquema estructural de las Formaciones del Oligoceno y travertinos del Pleistoceno en las Cuencas de Marsella-Aubagne.*

Studied area - Geological framework

The geology of the Marseille-Aubagne area consists of a Mesozoic basement (Triassic to Late Cretaceous) covered by post-Neogene basins (Oligocene to present day).

The basement was deformed during the Pyrenean-Provençal tectonic events which began in the Late Cretaceous (Maastrichtian event) and ended by the Late Eocene (the Bartonian tectonic event).The last sea campaigns of 2007 to 2012 showed that the Mesozoic basement is carried onto the continental plate (Tassy, 2012), south of the Calanques massif.

With respect to the geological and geographical properties, three separate basins have been distinguished in the Marseille-Aubagne (Fig.1): the Jarret basin to the north, the Prado basin to the south and the Aubagne basin to the east

They contain a thick pile (up to 1,000m) of detritic sediments belonging to the Oligocene and made up of breccias, argillites, sandstone and conglomerates (puddingstone) covered by breccias, argillites and travertines deposited between the Miocene and the present day. A detailed lithostratigraphy of the basins is presented in Figure 4 of the Nury *et al.* paper (this issue). Deposits are flat, except a part of the Oligocene formations. Furthermore, the Jarret basin continues into the bay of Marseille.

Nury, (1988) described an almost stratigraphically complete Oligocene succession from the base of Rupelian to the top of Chattian. But structurally, Guieu, (1977) and Nury, (1988) distinguished only two basins separated by a horst named the "Garde-Allauch horst". The latest research (Nury *et al.,* 2013) distinguished three separate basins, each having its own stratigraphic succession. The Rupelian grabens have a NNE-SSW to NW-SE extension, whereas the Chattian grabens are WSW to ENE. All of these basins have a similar sedimentology with fluviatile deposits to the south and lacustrine sediments to the north. Similar sedimentologic features have also been encountered in the adjacent Late Cretaceous basins. These characteristics are bounded to the Oligocene paleogeography which includes an elevated Pyrenean-Provencal chain to the south and several alpine basins to the north.

The latest research performed in the frame of the geological map revision (Villeneuve *et al.,* in press) have evidenced, both on land and in the sea, that a large part of the Rupelian formations exhibit dips between 30° to 90°, whereas the Chattian formations have low dips (0 to 30°).

These observations have led us to consider a tectonic event at the end of the Rupelian.

Results

We differentiated three kinds of folding but only the first two are recorded to an Oligocene event: TC-1 and TC-2. TC-1 which provides SW-NE metric to kilometric folds (P1) and TC-2 (P2 folds with N-S trending axes) reworked the P1 folds.

The dipping in the three basins

Figure 2 shows some characteristic outcrops. We can see that bedding (S0) exhibits a variably dipping between 30° to 90°, noticeably in the Prado and Aubagne basins as well as in the "Maurins" area (east of the Jarret basin). On the contrary, the bedding of the L'Estaque and Basse Bedoule limestone as well as the Joliette argillites presents a slow dipping (from 0 to 20°).

All the formations with strong dipping belong to the Rupelian (photos a,b,c,d,e,and f), whereas the formations with low dipping belong to the Chattian (photos g and h). An exception is visible in photo i where the formations belong to the Early Rupelian age.

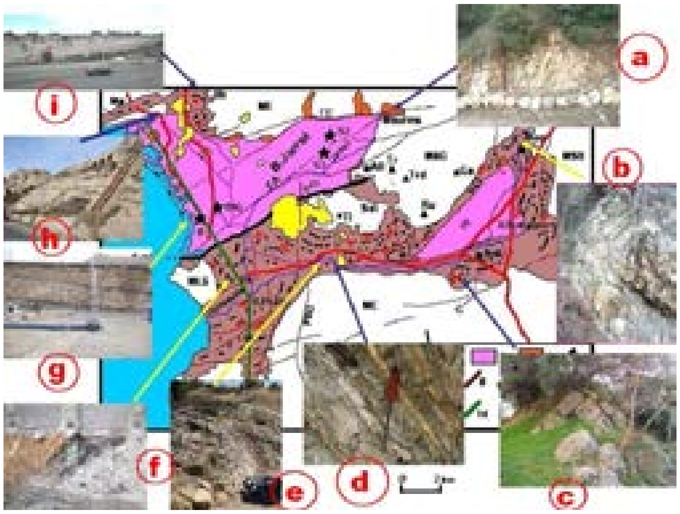

Figure 2. The main Oligocene facies in the Marseille-Aubagne basin. Except in the Maurins area, the Oligocene formations outcropping in the northern part present an almost horizontal bedding, contrary to those cropping out in the southern part. Legend: see in Fig.1. Photos: a)-Les Maurins, b)-St Charles, c)-South of Aubagne, d)-Water castle (St Marcel), e)-Valvert, f)-Parc du centenaire, g)- La Joliette, h)- L'Estaque, i)-La basse Bedoule.

Figura 2*. Las principales facies Oligoceno de la cuenca Marsella-Aubagne. Excepto en la zona Maurins, las formaciones del Oligoceno que afloran en la parte norte presentan una disposición casi horizontal, al contrario de aquellas que afloran en la parte sur.*

Deformations in outcrops (metric scale)

In the Jarret basin

The most intensive deformations are recorded in the Maurins valley, north-east of Allauch (Fig. 2a). Breccias and limestone ascribed to the Early Rupelian exhibit a sub-vertical dip. A syncline was observed in the Canal de Provence gallery (Fig. 3a). The Early Rupelian formations are capped by sub-horizontal breccias correlated to the Late or post Chattian period. However, owing to their location along a main fault, these deformations may also be related to a slump system operating during the deposition of the limestone. But we notice that the adjacent most likely Chattian Piedautry marls are undeformed, although the underlying limestone has a strong S0 dipping close to the city of Allauch.

In the Prado basin

A trench recently dug in the "XXVI Centenary park" shows beds where the dipping varies from 30° to 45°. Nevertheless, the most representative cross section is that of the Emissaire II sewer (the southern part of the Emissaire I, Fig. 1), between the Huveaune River and the Marseilleveyre massif) studied by Weydert and Nury (1978) and interpreted in Figure 3b. From the south to the north, this cross-section goes successively through the "Vert plan" anticline, The "Mazargues" syncline, the "Paoli-Calmettes Institut" anticline and the "Ste Marguerite" syncline.

Remarkably, another cross section was set up by G. Denizot (1952) in the Barasse valley. A gallery allows us to underline the thrusting of the Mesozoic basement over the Early Oligocene formations (Fg. 3c). With respect to the Oligocene succession the underlying formations should be in a reverse position.

In the Aubagne and Destrousse basins

The red argillites with green limestone lenses of the Destrousse formation (Middle Rupelian) show dips of 20° to 45°. At "Pont de Joux" (North of Roquevaire) these red argillites are strongly folded and the eastern end of the "Etoile massif" is locally thrusted over these red argillites. The Gastaude cross-section (Fig. 3d) shows a normal fault between the "La Gastaude "(Rupelian p.p.) and the "La Royante" (Chattian p.p.) formations.

The geological cross-sections (kilometric structures)

The P1 folds (Fig. 4) are in the Aubagne basin: The St-Jean de Garguier syncline, the Pont de l'Etoile anticline, and the Donomagis syncline. The main P1 folds in the Prado basin were already delineated above (Fig. 3b). In the Jarret basin the folded structures are located on the northern part of the Salette and Allauch massifs. On the contrary, the Rupelian formations located on top of the Salette massif and the Marinier area (on top of the Etoile massif) were slightly deformed.

The Wulff diagrams *(upper hemisphere)*

The diagrams which take into account the poles of bedding surfaces (S0) show the mean orientation of deducted P1 folds in the lower formations (Fig. 5a) and the bedding poles from the Cap Janet –Merlan formation in Figure 5b.

Bedding poles indicate fold axes oriented SW-NE in the lower formations (Rupelian) but no specific orientation in the upper formations (Chattian). In Figures 5a the scattering of poles of bedding (S0) indicate a post TC-1 deformation called TC-2. In fact, TC-1 folds are reworked by folds with N-S to NNW-SSE trending axis. This suggests a reworking of the P1 fold axis before deposition of the Chattian formations.

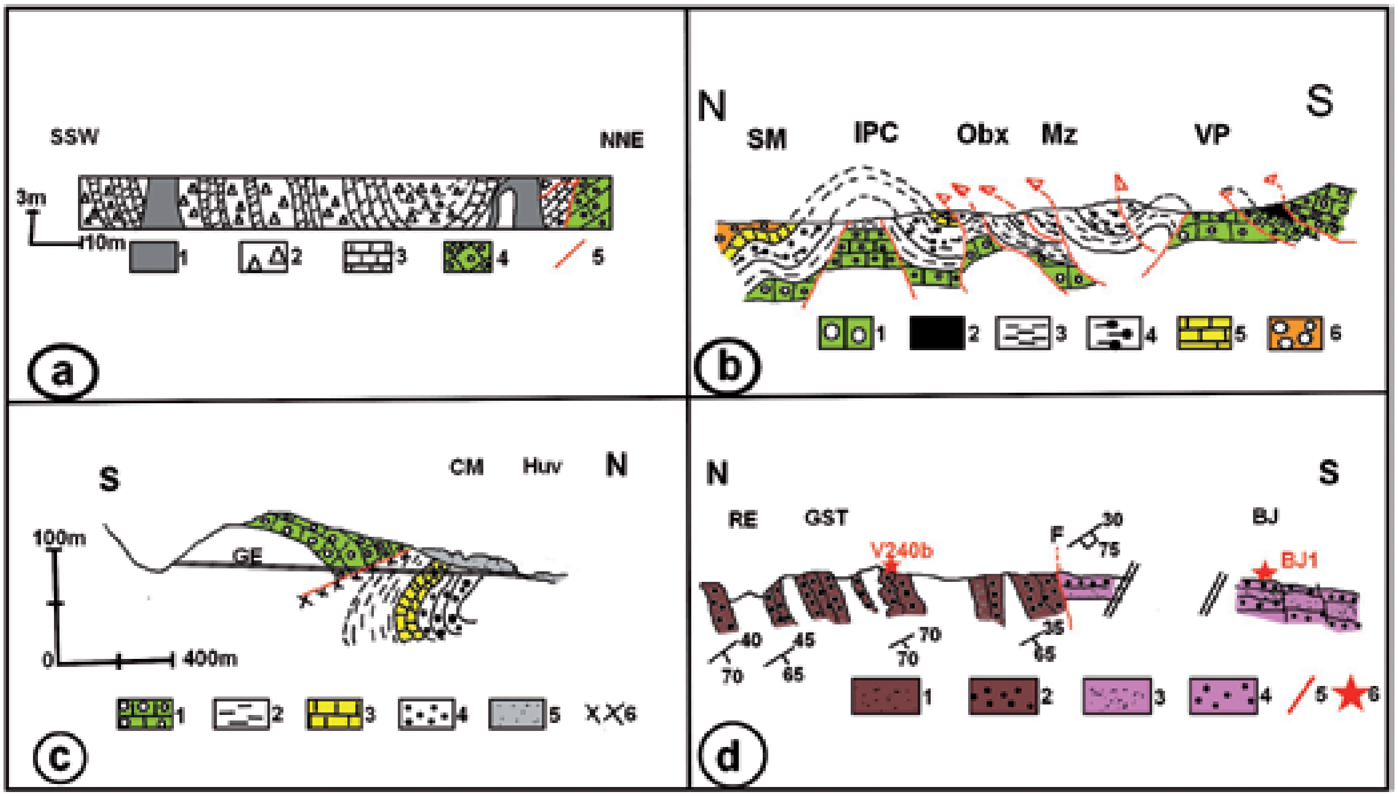

Figure 3. Examples of deformations in the field. a- Cross section along the "Canal de Provence" gallery in Maurins. 1- Concrete, 2-Breccias of limestone, 3- Laminated limestone, 4- Urgonien basement. b- Cross section along the gallery of the "Emissaire n°II": SM-Ste Marguerite, IPC- Paoli-Calmettes Institute, Obx- Mazargues Obelisque, Mz-Mazargues, VP-Vert plan. 1- Mesozoïc basement, 2- limestones with « striatelles », 3- St Marcel formation (argillites), 4- St Marcel formation (Poudingues), 5- Les Camoins formation (limestone), 6-Poudingues. c- Cross section of the La Barasse, CM- Marseille channel, Huv-Huveaune River, GE-Evacuation gallery. 1- Urgonian (Mesozoïc basement), 2- St Marcel argillites, 3- Les Camoins formation (limestone), 5-Poudingues of the "La Valentine formation", 6- Mylonitic breccia. The succession of the oligocene formations seems to be reversed. d- Cross section La Gastaude / Bonne Jeanne. GST- La Gastaude formation, BJ- La Bonne Jeanne formation. 1-sandstone with ripples-marks of the La Gastaude formation, 2-Poudingues of the La Gastaude formation, 3- Sandstone with cross bedding of the La Royante formation, 4-Poudingues of the La Royante formation, 5-Fault and 6-Samples for radiometric dating.

Figura 3*. Ejemplos de deformación en el campo. a- Corte a lo largo de la galería del "Canal de Provenza" en Maurins. b-Corte a lo largo de la galería del "Emisario no. II". c- Corte de la Barasse. d. Corte de La Gastaude/Bonne Jeanne.*

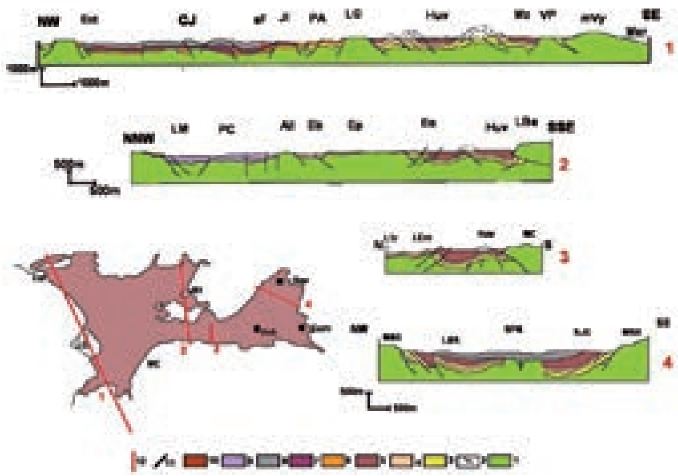

Figure 4. Main cross sections in the Marseille-Aubagne basin. Cross sections: 1-Cross section Le Marinier-Marseilleveyre, 2-Cross section Mordeau-la Barasse, 3-Cross section la Penne sur Huveaune-C, 4- Cross section Lascours - St Jean de Garguier. Legend : 1- Mesozoic basement, 2-Slope breccias 3-Le Marinier and St Marcel formations, 4- Les Camoins formation, 5-La Valentine and La Gastaude formations, 6- St André- St Henri formation, 7- La Porte d'Aix formation, 8-Cap-Janet Merlan and La Royante formations, 9- Piedautry formation, 10- Mourepiane formation (=Mordeau or Étoile breccias), 11- faults, 12- Fournier borehole.

Figura 4*. Cortes geológicos principales en la cuenca Marsella-Aubagne.*

Bay of Marseille structures

Pantaine (2010) observed several large anticlines and synclines structures on the Marsolig seismic profiles. The seismic profile interpreted by Pantaine (Fig. 6) is located in the southern part of the bay of Marseille and shows large folded structures in post basement materials that are correlated to the Oligocene formations. The structures observed in this seismic section were compared to those of the Emissaire II cross-section (Fig. 3b) drawn by Weydert & Nury (1978). The structures in Figure 6 may be linked to the on-land P1 folding.

In contrast, Pantaine (2010) showed that there are only a few folded structures in the northern part of the bay of Marseille. Just one syncline is presented with an equatorial axis going through the Joliette area. Formations cropping out in the core of the syncline can be correlated to Cap Janet-Merlan formation (Late Chattian) as verifed by two deep boreholes: the Fournier and the Gaz, both located in St Mauront (Fig. 1). The off-shore observations enhanced those on land.

Types of folding

Three different tectonic imprints have been considered apart from the distensive ones evidenced by Hippolyte *et al.* (1993).

TC-1. This event provides the P1 folding which may have different shapes. To the north, in the Marinier and the Basse-Bedoule areas, the flanks

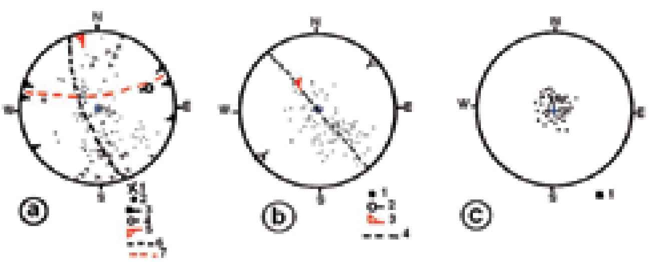

Figure 5. Wulff diagrams (upper hemisphere): a) and b) axis in the la Gastaude formation : 1-poles of bedding (S0) in the la Gastaude formation, 2- P1 axis measured , 3- P2 axis measured, 4- P1 envelope folds. c)-in the Cap Janet –Merlan formation. 1- poles of bedding (S0).

Figura 5*. Diagramas Wulff (hemisferio superior): a) y b) Eje de la Formación La Gastaude: 1-polos de estratificación (S0) en la Formación La Gastaude, 2- medida eje P1, 3- medida eje P2, 4- pliege sobre P1. c) En la formación Cap Janet -Merlan. 1- Polos de estratificación (S0).*

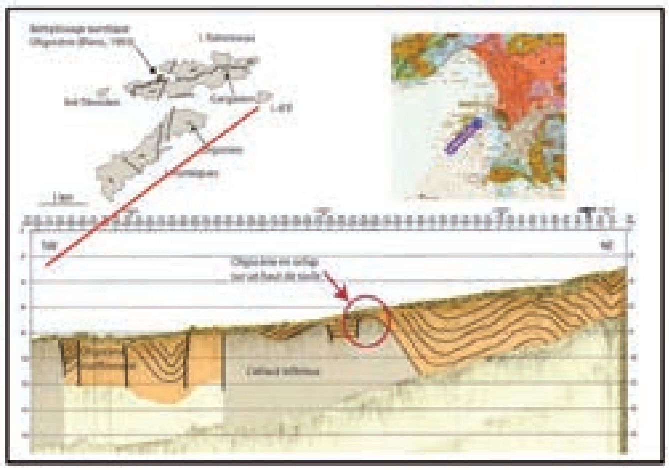

Figure 6. The folding of the Oligocene formation in the bay of Marseille (southern part) according to the Marsolig seismic profile (Pantaine, 2010 modified). The Oligocene formations occupy several SW-NE troughs on the eastern margin of the Frioul islands. Gentle folds in these Oligocene channels are underlined.

Figura 6*. El plegamiento de la formación del Oligoceno en la bahía de Marsella (parte sur) de acuerdo con el perfil sísmico Marsol (Pantaine de 2010 modificado). Las formaciones del Oligoceno ocupan varios canales SW-NE en el margen oriental de las islas de Frioul. Los pliegues suaves en estos canales del Oligoceno están subrayados.*

of the folds have a very slow dipping and the folds are open, whereas in the Maurins or in the Gastaude areas the flanks may be vertical and the folds tightly formed. These differences led our predecessors to deny a global tectonic event but rather to consider a local answer to post-Oligocene stress. However, in our opinion, the discrepancies in the degree of deformation are more likely to be related to the local weakness of basement rather than to a local stress. Thus, deformations are stronger close to the fault zones (La Gastaude, les Maurins) than on top of a rigid basement horst, such as in the Marinier or in the Salette horst. The heterogeneity of deformations is more related to the heterogeneity of the basement than to the diversity of tectonic stress. Nevertheless, all the Rupelian formations are more or less affected by one single tectonic event.

TC-2- Most of the P1 fold axis show an important dipping of 20° to 40°, whilst changes in direction are related to an E-W shrinking These changes are associated to folds with N-S trending axes that can be observed in the Basse Bedoule (northern area), or in the Camoins area. This folding is not important (slight curvatures) and the lateral shrinking is assumed to be weak.

TC-3- This event is linked to off shore synclines evidenced by Pantaine (2010), in the northern part of the Marseille bay and off Carry le Rouet. The cores of these structures were filled by Miocene sediments. Therefore, these structures are obviously post Oligocene. As we did not find similar structures on land, we consequently do not have any information on the age and tectonic origin of these folds (either compressive or distensive regime). However, this tectonic event may be related to the compression event evidenced in the "Étoile breccias" by Hippolyte *et al.* (1993). A NW-SE stress direction is supposed for TC1 and an E-W stress direction is deduced for TC2.

Both TC-1 and TC-2 are associated to provide the suspected Intra-Oligocene compressive event. Accordingly, TC-3 is excluded from this event.

Dating of the TC-1, TC-2 and TC-3 tectonic events

-Relative dating. At first, each deformation was ranked with respect to another one. TC-1 is supposed to have been reworked by TC-2 and thus is obviously older, although both are unconformably capped by the Chattian formations.

TC-3 is likely to be younger than the Cap Janet-Merlan formations (Late Chattian) and also younger than the Early Miocene strata, which set in the core of the off-shore synclines. A Langhian compressive event mentioned for a long time by various authors in the Marseille area may be acceptable for TC-3.

-Chronostratigraphic dating. Within a new stratigraphic chart (Nury *et al.,* 2013) that is supported by six groups of fossils, two stratigraphic gaps are evidenced. The older one occurs during the MP 24 zone of the mammalian scale (Emersheim zone) during the Late Rupelian and the younger one is attributed to the MP 27 zone, at the end of the Early Chattian. One of these gaps may be linked to the compressive tectonic event above mentioned. Unfortunately, we do not know if the gaps are related to emersive periods or to a lack of reliable fossils.

- *Radiometric dating.* In order to use another approach, two samples were selected to date their inherited zircons. One comes from the deformed La Gastaude formation (V240b) and the second from the flat lying "La Royante" formation (BJ1). The samples sites are separated by a normal fault (Fig. 3d). In order to differentiate the two samples only zircons younger than 40 Ma were considered for interpretative purposes.

Methods

Heavy minerals were separated from 1 to 2 kg of crushed sample material using LST (lithiumheteropolytungstate in water). This was followed by hand-picking of zircons under a binocular microscope. At least 120 zircons of each colour, morphology and size were randomly selected in order to get a representative sample set (Fedo *et al.,* 2003; Link *et al.,* 2009). Prior to cathodoluminescence (CL) imaging using scanning electron microscope (SEM) techniques, the samples were mounted in resin and polished to approximately half of their original thickness. The zircons were then analysed for their U-Th-Pb content by applying LA-ICP-MS at the Senckenberg Naturhistorische Sammlungen Dresden (Gerdes and Zeh, 2006 ; detailed information with respect to the instruments setting can be found in Table I of the supplementary content). Finally, calculations were done utilising a customised EXCEL spreadsheet developed by Axel Gerdes (Johann-Wolgang-Goethe-Universität, Frankfurt am Main). The results are displayed using l'Isoplot/Ex 2.49 (Ludwig, 2001) and AgeDisplay (Sircombe, 2004). If necessary, correction of common-Pb was carried out, based on the interference- and background-corrected 204Pb signal and a model Pb composition (Stacey and Kramers, 1975). Judgement of necessity for correction depended on whether the corrected 207Pb/206Pb lay outside the internal errors of the measured ratios. An interpretation with respect to the obtained ages was done for all grains within a range of 90-110 % of concordance (e.g. Meinhold *et al.,* 2011). Discordant analyses were generally interpreted with caution. Further details on the methods can be found in the supplementary material.

Results

*V240, Aubagne basin, La Gastaude formation, Eoures road (*Fig. 7). Of this sample 124 zircon grains were analysed. Most of the grains (~84 %) have internal textures related to magmatic crystal growth, but only a few of them with characteristics related to late- or postmagmatic influences (Corfu *et al.,* 2003). The other 16 % display metamorphic overprints of all stages. Altogether, 68 of the 124 zircons measured for U-Pb age determination, yield concordant ages between 28 ± 1 Ma and 2632 ± 17 Ma. The main peaks are at 29, 305, 450, 500, 575, 672, and 999 Ma (Fig. 7a, Tab. II) with some grains in between. Older grains occur at ca. 1060 to 1140, 1660, 1870, 1990, 2030, 2390, and 2630 Ma. The concordia age is at 28.74 ± 0.54 Ma and was calculated from the youngest grains with ages at 28 ± 1 and 29 ± 1 Ma. Obtained Th/U ratios of the concordant grains are in an interval from 0.01 to 0.93, with most of them showing values from 0.1 to 0.6.

BJ1, Aubagne basin. La Royante formation, la Bonne Jeanne road. (Fig. 8). A total of 132 zircons were studied from sample BJ1 The internal texture is mostly magmatic and only a few of these grains exhibit late to post-magmatic re-crystallisation or convolute zoning in the sense of Corfu *et al.* (2003). The remaining 17 % of the grains clearly show metamorphic overprint from sector and fir tree zoning to total homogenisation. Of the 132 zircon grains analysed for age determination, 80 display concordant ages ranging between 27 ± 1 Ma and 3243 ± 10 Ma. Larger age populations cluster around 288, 314, 352, 451, 609, 667, 782, 1000, and 2004 Ma with some grains occurring in between (Fig. 8, Table I). Some older grains are at ca. 2070, 2100, 2585 to 2700, and 3150 to 3240 Ma. An age of 27.40 ± 0.51 Ma may be calculated from the two youngest concordant grains. The Th/U ratios of the concordant grains range from 0.02 to 3.13, with most of them between 0.2 and 1.

Radiometric dating on inherited zircons extracted from sandstone and conglomerates (poudingues) of the "La Gastaude" formation indicates a post 28.7 Ma age for deposition and thus for the tectonic event which has folded these rocks. But, the chronostratigraphic dating of the "Porte d'Aix" argillites indicates an Early to Middle Chattian for sedimentation.

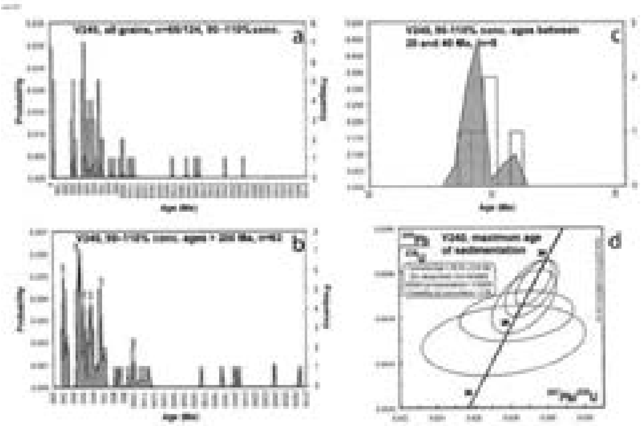

Figure 7. Datings on zircons from sample V240b (La Valentine formation). Binned frequency and probability density distribution plots for all concordant grains (a), for all grains older than Cenozoic (b), and for the youngest zircon age population (c). Figure d shows the concordia plot of the grains which were used to calculate the maximum age of sedimentation.

Figura 7. *Dataciones sobre circones de la muestra V240b (Formación La Valentine). Frecuencia agrupada y gráficas de distribución de densidad de probabilidad para todos los granos concordantes (a), para todos los granos más antiguos que el Cenozoico (b), y para la población en edad más joven de circones (c). Figura d muestra el gráfico de concordia de los granos que se utilizaron para calcular la edad máxima de sedimentación.*

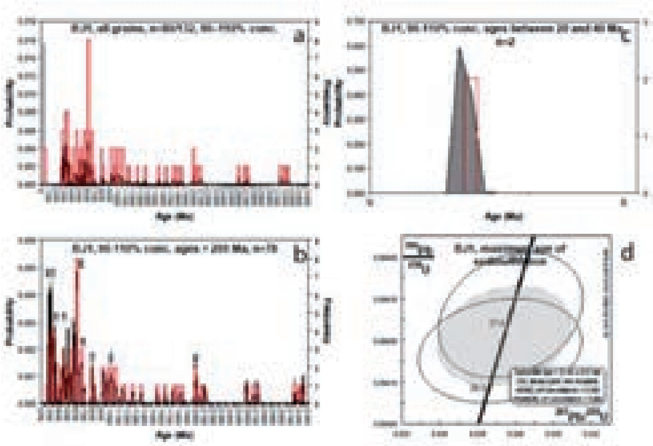

Figure 8. Datings on zircons from sample BJ1 (La Royante formation). Binned frequency and probability density distribution plots for all concordant grains (a), for all grains older than Cenozoic (b), and for the youngest zircon age population (c). Figure (d) shows the concordia plot of the grains which were used to calculate the maximum age of sedimentation.

Figura 8. *Dataciones sobre circones de la muestra BJ1 (Formación La Royante). Frecuencia agrupada y gráficas de distribución de densidad de probabilidad para todos los granos concordantes (a), para todos los granos más antiguos que el Cenozoico (b), y para la población en edad más joven de circones (c). Figura (d) muestra el gráfico de concordia de los granos que se utilizaron para calcular la edad máxima de sedimentación.*

Hence, taking into account the Rupelian / Chattian limit at 28.1 Ma (Cohen *et al.,* 2013), the folding of the “La Gastaude” formation may be coeval with the deposition of part of the St-André-St-Henri formation (Late Rupelian to Early Chattian). That may be acceptable by considering the first opening stage of the Jarret basin as a foreland basin with respect to the Oligocene Huveaune belt. The second stage clearly suffered an extensive trend.

Discussion and interpretation

TC-1 and TC-2 in the local Oligocene tectonic framework. Hippolyte *et al.* (1990 and 1993) have described five stages related to the extensive regime: two in the Rupelian age and three in the Chattian age.

During the Rupelian age the extensive regime caused a stress direction that was oriented NW-SE, while in the Chattian they were oriented successively: NE-SW, NNE-SSW and finally NNW-SSE. These tectonic events can be correlated to five sedimentary cycles.

With respect to these tectono-sedimentary stages, TC-1 and TC-2 should be inserted between the second and the third stage of Hippolyte *et al.* (1990 and 1993).

TC1 and TC-2 in the Provence-Oligocene framework. The main Oligocene basins in Provence are shown in Figure 9. Of them, the largest ones are located in the western part of the “Durance-Aix fault” including, noticeably, the Aix and Manosque–Forcalquier basins. In the eastern part of the fault, the three Marseille-Aubagne basins, as well as several tiny basins scattered in the northern Var area, can be found. The lowermost stages of many basins in northern Var began with Eocene deposits covered by Oligocene sediments. Concerning the basins located in the western part of the Durance fault, no major unconformity has been found except in the disputed St- Pierre les Martigues trough. In this basin, Nury (1972) and Guieu (1973) showed an intra Rupelian thrust fault, but recently, Andreani *et al.* (2010) did not support this interpretation, although Philip (2012) pointed out a strong dipping in the Early Rupelian in the Baumaderie area (south of the St-Pierre les Martigues basin). However our own observations in this basin indicate a low angle unconformity between the Rupelian limestone and the Chattian breccias. Despite these local observations, we doubt that the intra-Oligocene tectonic event, evidenced in the Marseille-Aubagne basins, has affected the western areas of the Durance fault.

On the contrary, in regions east of the Durance fault, this intra Oligocene tectonic event has been suggested by several authors. Cornet (1964) favoured a “phase tectonique Oligocène d’origine profonde” supposed as intra-Oligocene. Aubouin and Chorowicz (1967) linked the Late Pyrenean-Provence thrusts to a hypothesised intra-Oligocene tectonic event. Later on Touraine (1966, 1967, 1969, 1973 and 1976) assigned a “post-Stampian” age to the unconfomity in the Varois basins. According to him several “post-Stampian” (Late Rupelian) compressive tectonic events are preceded by a Sannoisian (Early Rupelian) extensive regime. He also demonstrated (Touraine, 1976) that the N-55 E stress direction of the compressive event provided many folds and thrusts as in the Sannoisian Bourdas syncline, in the La Combe syncline (Stampian poudingues) and in the Montmeyan trough. He deduced the sliding of the Jurassic limestone over the Stampian “sables bleutés” and conglomerates. Despite a direct covering by Miocene continental sediments (Vindobonian ?), Touraine correlated the intra-Oligocene compressive events to an Early alpine tectonic activity. Due to the lack of Chattian deposits we are not able to confirm this hypothesis. With our present knowledge it is not possible to propose a global and consistent tectonic model.

Hypothesis on the TC-1 and TC-2 origin. Intra-Oligocene tectonic events were widely evidenced in southwestern Europe

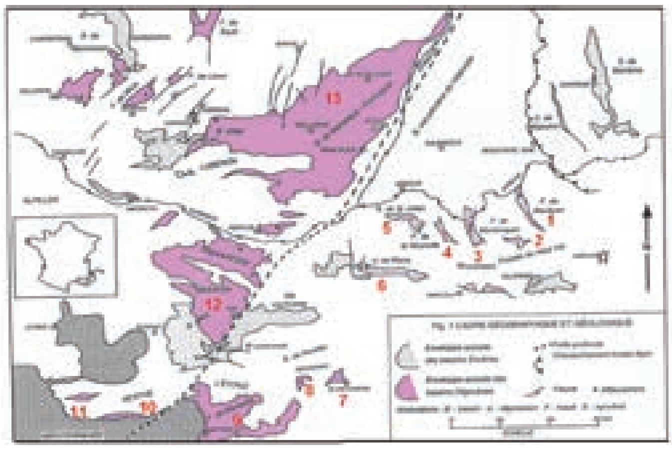

Figure 9. The main Eocene and Oligocene basins in Provence. Dashed line = Durance and Aix en Provence fault which extends to the bay of Marseille. 1- Pyrenean-Provence belts, 2- Eocene basins, 3- Oligocene basins, 4- Mediterranean Sea
1- Bauduen graben, 2- Haut-Var graben, 3- Montmeyan graben, 4-Mourotte graben, 5- St-Julien graben, 6- Rians basin,7-St Zacharie basin, 8-Auriol basin, 9-Marseille-Aubagne basins, 10-Carry le Rouet basin, 11-St Pierre basin, 12-Aix basin, 13- Manosque basin.
Figura 9. *Las principales cuencas del Eoceno y el Oligoceno en Provenza.*

In the southern part of the Aquitanian basin Gely and Sztrakos, (2001) gave evidence for folding and thrusting ascribed to a Rupelian tectonic event.

In the Iberian belt (Central Spain), Geel (1995) pointed out a tectonic unconformity between the deformed Rupelian formations and sub-horizontal formations attributed to the Early Chattian. This unconformity is also correlated to an intra-Oligocene tectonic event.

Despite similarities in timing and framework, it is difficult to produce a coherent and gobal model to enhance this tectonic event. In addition, there is a lack of remnants confirming this intra-Oligocene event in the "West European rift" which separates the Pyrenean and Iberian zones from eastern Provence and the Alps, and thus prevents any comparisons in both areas.

Figure 10. Oligocene paleogeographic sketch map with the Téthys subduction underneath the Iberic margin (after Oudet, 2008, modified). a) - Northwestern margin of the Tethys ocean: 1- Main strike slip faults, 2-Main normal fault, 3-Main thrust fault, 4-Marine transgressions, 5- Tethys oceanic domain, 6- Tethys deep water domain, 7-Tethys shallow water domain, 8-Coastal range, 9-Continental areas. Ka- Kabylian ranges, Sa-Sardinia, Co- Corsica, Vt-Valence trough, GL- gulf of Lion. b)-Oligocene Provencal domain: BA-Arlesian basin, BM-Marseillais basin, BV-Villeneuve basin, GF-Grand Faraman basin, LN- Nerthe uplift.

Figura 10*. Esquema de mapa paleogeográfico del Oligoceno con la subducción Tetis debajo del margen ibérico (después Oudet, 2008, modificado).*

Hence, we are thinking about a movement of the volcanic arc with respect to the back-arc basin along the Tethysian active margin (Fig.10) in order to explain the intra-Oligocene tectonic event in eastern Provence. In fact, the Provence-Oligocene basins are in line with the back-arc basin separating the south Pyrenean block from the Corso-Sarde block. This kind of movement is well known in active margins and especially assumed for the Indonesian margins which are very similar to the Mediterranean model (Villeneuve *et al.,* 2010). When the volcanic arc moves away from the continent, the back-arc basin opens and, on the contrary, when the volcanic arc converges to the continental block, the back-arc basin shrinks. We expect that a similar situation may have taken place. This would explain the local shrinking of the Marseille-Aubagne and Varois basins which predate the opening of the Western Mediterranean Sea.

Conclusions

New research, carried out in the course of updating the geological map, has evidenced an intra-Oligocene compressive tectonic event affecting the three Marseille-Aubagne basins. The deformed sediments belong to the Rupelien, whereas the overlying sub-horizontal formations are assumed to be Chattian in age. Thus, this tectonic event has been dated at the time limit between the two Oligocene ages. Radiometric dating on inherited zircons extracted from samples taken from formations located below and above the unconformity is consistent with this deduced age.

This event, already described in the neighbouring basins located in the Var, was disputed in the Marseille-Aubagne basins owing to the large variability of the deformations inferred from this tectonic event. Previous authors favoured a model including local reactions of the Oligocene sediments to post Oligocene tectonic events. Nevertheless, this tectonic event has not yet been evidenced to the west of the SSW-NNE Durance fault.

With respect to the location of this tectonic event and within the framework of a Tethys active margin, we believe that the deformations are related to the relative movements of the volcanic arc compared to the back-arc basin which is supposed to have been connected with the Marseille-Aubagne basins.

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