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# New insights on the Marseille-Aubagne Oligocene basins (France)

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ABSTRACT

The Marseille-Aubagne Basins, which extend from Marseille to Roquevaire, occupy more than fifty per cent of the Marseille-Aubagne geological map, with approximately one million people living in this area. Despite this geological importance they are still poorly known. The first synthetic view was delivered in the 1935 geological map. Studied by Bonifay, the Quaternary deposits have been included in the 1969 geological map. Nevertheless, the Oligocene formations remained unmodified until Nury, who provided a lot of very detailed stratigraphic data. New studies have been carried out in the frame of the third issue of the 1:50,000 geological map. These studies allow us to distinguish between three different basins: the "Jarret basin" in the northern part, the "Prado basin" in the southwestern part and the "Aubagne basin" in the eastern part. Each of them contains its own stratigraphic succession, including several formations from the Rupelian to the Chattian. Globally, the Lower to Upper Rupelian formations are tectonically deformed, whilst deposits from the Latest Rupelian to the Latest Chattian show only slight deformation. Thus, two main geodynamic stages have been distinguished: the first beginning with the Early Oligocene extensive regime leading to the opening of NNE-SSW troughs all over the European platform and, the second, beginning with a NNW-SSE extensive regime coeval with the Western Mediterranean rifting. The key point that separates these two stages from each other is a possible Late Rupelian compressive regime. To sum up, this basin can be considered as a natural archive for the Oligocene events. Therefore, these basins should be considered as master pieces for the Oligocene palaeogeographic and geodynamic reconstructions.

Key words: Oligocene, Marseille-Aubagne basins, Western European rift, Western Mediterranean rifting

## *Nuevos conocimientos sobre las cuencas oligocenas de Marsella-Aubagne (Francia)*

*RESUMEN*

*Las cuencas de Marsella-Aubagne, que se extienden desde Marsella a Roquevaire, ocupan más del cincuenta por ciento del mapa geológico de Marsella-Aubagne con cerca de un millón de personas viviendo en la región. A pesar de su importancia geológica, aún son poco conocidas. La primera visión sintética fue llevada a cabo en el mapa geológico de 1935. Estudiados por Bonifay, los depósitos cuaternarios fueron* *incluidos en el mapa geológico de 1969. Sin embargo, las formaciones del Oligoceno no se modificaron hasta que Nury proporcionó una gran cantidad de datos estratigráficos muy detallados. Nuevos estudios han sido llevados a cabo en el marco de la tercera edición del mapa geológico 1:50 000. Estos estudios permiten distinguir entre tres cuencas diferentes: la «cuenca de Jarret» en la parte norte, la «cuenca del Prado» en la parte suroeste y la «cuenca de Aubagne» en la parte oriental. Cada una de ellas contiene su propia sucesión estratigráfica que incluye varias formaciones desde el Rupeliense hasta el Chattiense. De manera general, las formaciones del Rupeliense inferior a superior están deformadas tectónicamente, mientras que los depósitos del final del Rupeliense hasta el Chattiense superior sólo presentan una deformación leve. Por lo tanto, se han podido diferenciar dos etapas geodinámicas principales: la primera empieza con régimen distensivo en el Oligoceno inferior y conduce a la apertura de depresiones de dirección NNE-SSO a lo largo de toda la plataforma europea y, la segunda, que comienza con un régimen distensivo NNO-SSE coetáneo con el rifting del Mediterráneo Occidental. El punto clave que separa estas dos fases entre sí es un posible régimen compresivo en el Rupeliense más tardío. Para concluir, esta cuenca se puede utilizar como un archivo natural para los eventos del Oligoceno. Por lo tanto, estas cuencas deben ser consideradas como piezas maestras para las reconstrucciones paleogeográficas y geodinámicas del Oligoceno.*

*Palabras clave: Oligoceno, cuencas de Marsella-Aubagne, rift de Eupora occidental, rifting del Mediterráneo occidental*

## *VERSIÓN ABREVIADA EN CASTELLANO*

### ***Introducción y metodología***

*En Provenza (SE de Francia) se encuentran varias cuencas sedimentarias que contienen sedimentos del Oligoceno y cuyo emplazamiento sucede a la par que la cadena pirenaico-Provenzal (Fig. 1). Entre las más amplias se incluyen las cuencas de Marsella-Aubagne. Desde un punto de vista geográfico, hay tres entidades (Fig. 2): la cuenca del Prado (en el Suroeste), la cuenca de Aubagne (en el Este) y la cuenca de Jarret (al Norte).*

*Los datos previos sobre estas cuencas están basados en el mapa geológico de 1935 en donde se habían integrado los datos de Depéret, Repelin y Denizot. La parte de esta carta que considera estas cuencas fue utilizada, sin muchos cambios, en el mapa geológico de 1969. Después de esta fecha, la investigación se llevó a cabo por Nury quien estableció una estratigrafía correlacionable cuenca a cuenca y demostró que la sedimentación oligocena en el sur de Provenza estuvo esencialmente controlada por la tectónica extensional y por las variaciones climáticas. En 1968 y 1977, Guieu atribuyó la existencia de una cuenca en Marsella a la rotura tectónica en la parte posterior de la cadena de La Estrella y no a la tectónica compresiva como había sido considerado por consejo de Cornet. Desde el año 2001, esta investigación se recoge como parte de la tercera edición del mapa geológico Marsella-Aubagne (en curso). Son estos nuevos datos que conducen a nuevas interpretaciones el objeto de esta publicación.*

### ***Resultados y discusión***

*Estructura de las cuencas. En el diagrama estructural (Fig. 3), las cuencas del sur y del este no presentan las mismas características estratigráficas, sedimentarias y estructurales que la cuenca del norte (cuenca de Jarret). Por ejemplo, la cuenca sur del Prado y la cuenca oriental de Aubagne están deformadas por pliegues abiertos mientras que la mayor parte de las formaciones de la cuenca de Jarret no tienen apenas deformación. Por otra parte, se aprecia en este esquema que las direcciones estructurales de las cuencas del Prado y Aubagne están orientadas SSO-NNE a SO-NE, mientras que las características estructurales de la cuenca de Jarret se orientan OSO-ENE.*

*La sucesión litoestratigráfica establecida tiene en cuenta tres unidades geológicas reconocidas. En cada una de ellas se puede distinguir un grupo estratigráfico formado por varias formaciones, algunas de las cuales se subdividen en miembros. Así, se diferencian el grupo de Jarret, el grupo del Prado y el grupo de Aubagne (Fig. 4). Dado el carácter fuertemente continental de los depósitos, es arriesgado aplicar una única estratigrafía sintética como se había hecho anteriormente. El grupo de Jarret comprende 8 formaciones, 3 en el Rupeliense y 5 en el Chattiense. El grupo del Prado incluye 3 formaciones, todas ellas pertenecientes al Rupeliense. De hecho, no se han encontrado fósiles característicos del Chattiense. El grupo de Aubagne (o serie sedimentaria de Aubagne) incluye seis formaciones, cinco con fósiles de edad Rupeliense y una de edad supuestamente Chattiense aunque no hay ninguna característica fósil que así lo indique.*

*Datos sedimentológicos. Un modelo sedimentario se ha definido y verificado en la mayoría de las cuencas. Los depósitos se interpretan como vinculados a un ambiente continental que va desde un medio ambiente predominantemente lacustre a un entorno principalmente fluvial. En general, se observa que los depósitos de tipo lacustre están localizados en los márgenes norte mientras que los depósitos groseros fluviales se encuentran en los márgenes sur, sea cual sea la cuenca considerada. Los medios de sedimentación corresponden a 4 tipos: 3 hábitats continentales (terrestre, de agua dulce, de salinidad variable), ampliamente representados en todas las cuencas del Oligoceno del sur de Provenza durante todo el período, y un hábitat marino costero al final del Oligoceno. El medio terrestre está marcado por la presencia de numerosos restos de vertebrados, moluscos, polen y esporas y de restos vegetales macroscópicos que marcan diversos niveles de altitud. Los hábitats de agua dulce fluviales o lacustres están marcados principalmente por moluscos gasterópodos hervíboros. Los medios de salinidad variable están indicados por moluscos mesohalinos (10 a 18°/00) que son los que mejor reflejan por norma general la existencia de este tipo de ambientes. También hay celentéreos sifonóforos, cuya presencia en abundancia dentro de un nivel demuestra la comunicación eficaz de la zona sedimentaria con el mar abierto. También da fé de la proximidad a la costa la presencia de foraminíferos litorales, ostrácodos, polen y esporas.*

*Datos paleontológicos y cronoestratigráficos. A pesar de que más de 60 nuevos lavados se han llevado a cabo para recoger microfósiles, sólo 3 nuevos sitios contienen fósiles para especificar las edades de las rocas que los contienen. Estos son: las arcillas y margas del Parque de XXVI° Centenario que contienen* Nitellopsis *(Tectrochara)* meriani, Lychnothamnus pinguis *y* Chara *sp. indicando el Rupeliense basal (formación de St-Marcel inferior); areniscas y argilitas de Mazargues (sitio de magasin Weldom) que contienen* Nystia chastelli *y* Brotia laurae *(gasterópodos)* Hydrobia *sp. así como* Leguminocythereis verricula - *scrobiculata (ostrácodo) que marcan el Rupeliense inferior y argilitas grises y blancas del boulevard Nédélec (formación de la Porte d'Aix), que contienen* Chara microcera *de edad Rupeliense terminal a Chattiense. Aun así sus indicaciones son valiosas porque ayudan a ubicar el periodo en los niveles básicos de las cuencas del Prado y de Jarret. Nuestro último trabajo nos ha permitido presentar una nueva escala cronoestratigráfica del Oligoceno de la cuenca Aubagne-Marsella gracias a las correlaciones entre las escalas de seis grupos de fósiles (Tab. I) en lugar de los cuatro usados anteriormente.*

*Edades radiométricas. Hemos datado los circones de origen detrítico (método U/Pb) contenidos en 6 muestras de areniscas y conglomerados. Estas muestras arrojan edades entre el Arcaico (3 Ga) y el Oligoceno (26 Ma). Aquí sólo vamos a hablar de las muestras con edades más jóvenes de 100 Ma. Algunas muestras contienen circones de edades comprendidas entre los 35 ± 1 Ma y los 27 ± 1 Ma (Fig. 5a) con una concordancia del 90 al 110%. Los 16 circones más jóvenes dan una edad «Concordia» en torno a 27.41 ± 0.22 Ma (Fig. 5b). Estos circones detríticos, que se atribuyen a los episodios volcánicos que acompañaron a los rifts de Europa occidental y del Mediterráneo, permiten datar hasta la fase tectónica intra-Oligoceno en las proximidades del límite Rupeliense/Chattiense.*

*Tectónica. Las formaciones geológicas (Fig. 6) muestran que los pliegues a gran escala están localizados en las cuencas del Prado y Aubagne. De hecho, las formaciones inferiores (Rupeliense) con buzamientos más importantes afloran principalmente en estas cuencas, mientras que las formaciones superiores (Chattiense), subhorizontales, cubren casi por completo la cuenca de Jarret. Esto demuestra que hay una discordancia entre estos periodos, la cual está, en nuestra opinión, generada por un evento tectónico de compresión situado hacia la mitad del Oligoceno y que podría estar relacionado con los movimientos relativos del arco volcánico de Córcega y Cerdeña y su cuenca trasarco.*

*Paleogeografía y evolución de cuencas. Al unir nuestras observaciones a las de Hippolyte et al., se pueden definir siete etapas de la evolución: tres estadios de relleno en el contexto de apertura de surcos, una etapa de deformación por compresión en el límite Rupeliense/Chattiense y tres etapas nuevamente en régimen distensivo durante el Chattiense.*

***Discusión e interpretaciones***

*Comparando la evolución de las cuencas de Marsella-Aubagne con la evolución del Suroeste de Europa durante el período Oligoceno se observa que: 1) las fosas del Prado y Aubagne están alineadas con el rift de Europa occidental (Fig. 7a) y son compatibles, desde el punto de vista de su estructura y su evolución, con las de Valencia, en España, y las de Alès, Limagne, Bresse y Alsacia en Francia, así como con las del Mar del Norte, 2) la fosa de Jarret, de orientación OSO-ENE, se rellenó posteriormente y es compatible con las fosas del rift del Mediterráneo occidental donde una rama meridional ha oceanizado hacia los 21 Ma debido a la deriva del bloque Corso-Cerdeño (Fig. 7b). La cuenca de Jarret debe haber sido una rama abortada del rift mediterráneo. Por lo tanto, en las cuencas de Marsella-Aubagne habría una relación con el rift de Europa Occidental en el Rupeliense y con la deriva del bloque de Córcega y Cerdeña en el Chattiense.*

## Introduction

Several sedimentary basins are located in Provence. They were filled coeval to the uplift of the Pyrenean-Provence mountain chain during the Oligocene. These basins are larger and occur more frequently to the west than to the east of the Durance-Fault (Fig. 1). With respect to their areal extent, the Marseille-Aubagne basins are the most important of the mentioned basins.

The Marseille-Aubagne basins are populated by approximately one million inhabitants and extend from Marseille to the foothills of the Saint-Baume Massif (Fig. 2), which is equal to more than 50 % of the area covered by the Marseille-Aubagne sheet of the French geological map (1:50,000). These basins are framed by the following massifs with an anticlokwise order: the Carpiagne Massif (south), the Sainte-Baume Massif (north-east), and the Allauch, Etoile and Nerthe Massifs (north).

From a geographical point of view there are three basin entities separated by the “horst” of Allauch: the Prado basin (SW), the Aubagne basin (E), and the Jarret basin (N).Their location is given in Figure 2. Oligocene sediments also crop out in several surrounding localities of the Marseille-Aubagne basins, such as the region of Bandol and Var (E), the Aix basin (N) as well as in the Nerthe area (W).

The complex tectonic framework of the entire area, the scarcity of terrestrial fossils, and the high amounts of built-up area hamper extensive studies. For the stratigraphically deeper parts of the 1935 geological map, which mainly contains Oligocene strata, Haug *et al.* (1935) proposed a synthesis based on only one stratigraphic scale as was commonly done at that time. However, the structural and sedimentological aspects remained poorly developed, even in more recent geological maps and notices (Guieu *et al.,* 1969), although the research done by Bonifay (1962) was already included in the post-Oligocene cover. Studies conducted by Nury (1988) and Hippolyte *et al.* (1990, 1991, and 1993) have partially filled this gap. However, those previous studies consider one only or two basins which were coeval filled.

Recent research conducted since 2001 in the frame of the third edition of the geological map allow a different interpretation. Owing to the strong variability of the sedimentation, even in a restricted area, we are now considering three separate sub-basins which correspond more or less to the geographical entities mentioned above.

While still ongoing, these studies have improved the basic understanding of the lithostratigraphic, structural, tectonic, sedimentologic, and geodynamic aspects of the Marseille-Aubagne and the adjacent Rouet and Destrousse basins. New data resulting from these studies has led to a re-interpretation of the geological context.

## Objectives and methods

This article aims to reconstruct the Oligocene evolution of the Marseille-Aubagne basins. The following

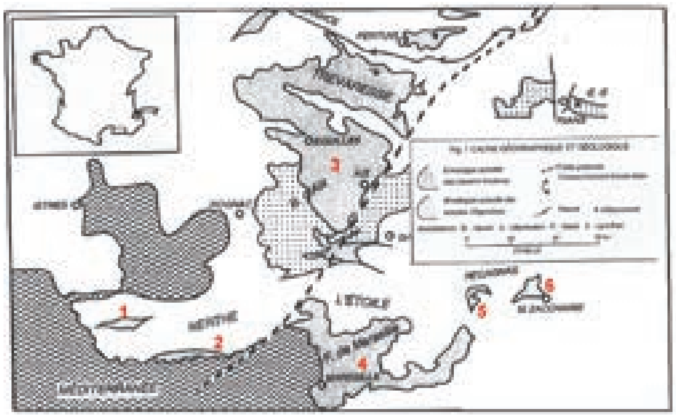

**Figure 1.** The main Oligocene basins around Marseille. 1- St-Pierre-les Martigues basin, 2- Rouet basin, 3- Aix-en-Provence basin, 4-Marseille basins, 5- La Destrousse basin, 6- St-Zacharie basin.
***Figura 1.*** *Las principales cuencas oligocenas alrededor de Marsella.*

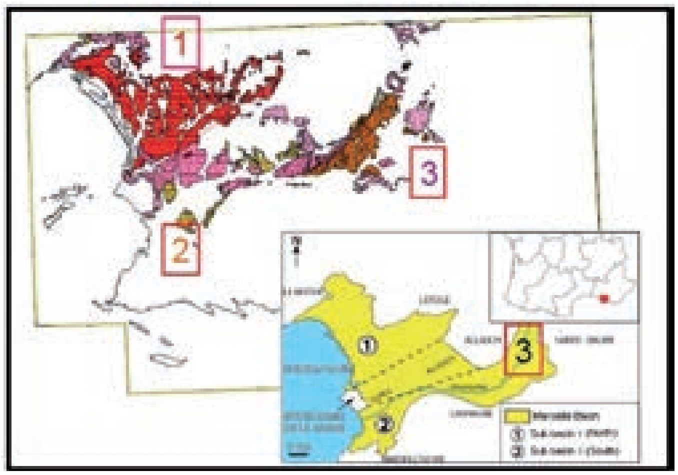

**Figure 2.** Structure of the Marseille-Aubagne basins: a) Oligocene outcrops in the Marseille-Aubagne basins, b) - Localisation of the 3 basins separated by la Garde-Allauch horst.1- Jarret basin, 2- Prado basin, 3- Aubagne basin. Yellow: Early Rupelian formations, Pink: Middle Rupelian formations, Red: Chattian formations in the Jarret basin, Orange: Chattian formations in the Aubagne basin.
***Figura 2.*** *Estuctura de las cuencas Marsella-Aubagne.*

events can be delineated with respect to their appearance: the termination of the Pyrenees-Provence orogeny, the western European rifting and the opening of the western Mediterranean. Due to a lack of subsurface data, this chronology had to be inferred exclusively from surface observations.

## Geologic setting and research history

The geological map at scale of 1:50,000 shows that the post-Eocene basins evolved in depressions which are surrounded by the massifs of the Pyrenees-Provence mountain chain, built at the end of the Paleocene. These mountains became a subject of extensive geological work at the end of the 19th and during the first decades of the 20th century (Bertrand, 1899; Haug, 1930). Intense and controversial discussions have finally ended due to a consensus reached by the thesis of Guieu (1967). This was not the case for the post-Eocene and in particular not for the Oligocene basins. The regions of the southern Provence covered by Oligocene sediments, mainly the Aix-en-Provence and Marseille-Aubagne basins, have been investigated for many years. A first systematic study concerning the Marseille basin was published by Depéret (1889), who compared its series with those of the Aix-en-Provence basin and concluded for an identical, “Lower Tongrien” age. In 1916, Répelin distinguished between the limestone of Marseille from the gypsum series of Aix. Finally, Denizot established his fundamental distinction of the Oligocene limestones of Marseille in 1920. Following the classification of this time, he separated the limestone of Piédautry from the Sannosien of L’Estaque and removed it to the Upper Stampian or Lower Aquitanian, thus, defining it to be time equivalent with the gypsum layers of Aix. The debate with Répelin (1930), who assumed the limestone of Piédautry to be of Latdorfian age lasted more than a decade and was not finished until the latter passed away in 1942. Denizot (1943) defined the Latdorfian, Stampian and Aquitanian as principally stratigraphic succession of the sedimentary units in the Aix-en-Provence, Marseille-Aubagne, and Saint-Zacharie basins. This classification was adapted for the regional geologic maps. Until the 1960s no new studies on the Oligocene of this region have been published. In his various works of structural geology and tectonics, Guieu (1968) reconsiders the relations between the Oligocene basins and the surrounding mountains. In 1968 and 1977, he attributed the existence of the Marseille basin to a fault at the backside of the Etoile Massif, at which tectonic activities recurrently moved the Mesozoic cover towards the north.

At that time, it was supposed, that all compressional movements in the western Provence took place during the Bartonian tectonic phase, which neither was attributed to the Oligocene, nor to more recent times, as was done for vertical movements. However, Cornet (1965) emphasised Stampian and terminal-Oligocene phases without any further precision. Nury (1964) began her first research using conventional stratigraphy, but changed around 1967 to the stratigraphy proposed by Rey (1966). Following the German and Belgian subdivision, the latter author suggested that sediments of Saint-Henri-Saint-André and the conglomerates of Marseille are of Chattian age. Other studies have been done throughout the Provence, e.g. Châteauneuf on pollen, Feist-Castel on charophytes, and Hugueney as well as Truc on mammals and molluscs. Disagreements between several specialists led to Nury’s decision, that molluscs are the most suitable for the mapping and correlation of the continental Oligocene strata.

Meanwhile, the interdisciplinary studies on the Oligocene-Miocene limit at Rouet, west of L’Estaque, were done at the Cap Janet sites (Colomb *et al.,* 1979). Finally, the surveying and mapping for the 1:25,000 geological map of the basins around Marseille was finished with respect to palaeontology (pollen, charophytes, mammals) and accompanying sedimentary and structural studies by Nury (1988). They allowed: 1) the set-up of an Oligocene stratigraphy which could be correlated throughout the basins and redefined the continuity of several gastropod species (Cavelier *et al.,* 1984); 2) to show, that the Oligocene sedimentation in the southern Provence was mainly controlled by large scaled tectonic events (Nury, 1984; Nury and Reynaud, 1986).

The numerous published estimations for the age of different Oligocene series of the Provence, made by several authors, were mainly caused by the exclusive use of either terrestrial molluscs or their relatives from brackish water. However, these organisms are used to trace changes in the composition of biotic communities and climatic conditions. An attribution to a distinct species is sometimes not possible due to significant changes in their shells.

## Results

### *Structure of the Oligocene basins*

Three different sub-basins have been recognised (Fig. 2), among them, the Aubagne basin to the east having a correlation to the northern Destrousse basin and to the western Prado basin. These last two

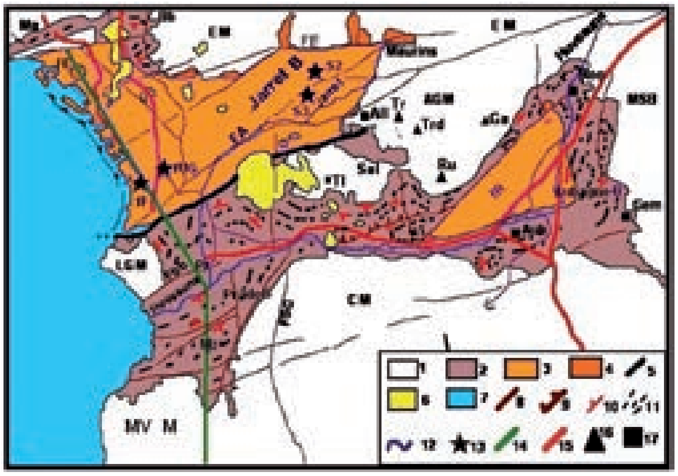


**Figure 3.** Structural scheme of the Marseille-Aubagne basins. EM-Etoile massif, AGM- Allauch–Garlaban massif, SBM- Ste Baume massif, CM- Calanques massif, MVM- Marseilleveyre massif, LGM- La Garde massif, Ma-Marinier, Bb-basse-Bedoule, All-Allauch, Tr-Tête rouge, Trd: La Treille, Ru-Ruissatel, Ga-Garlaban, Roq-Roquevaire, Gem-Gemenos, Aub-Aubagne, Mz-Mazargues, Pr-Prado, Tl-Trois Lucs, Sal-Salette, FE- l'Estaque fault, FEt- l'Etoile fault, FA-Allauch fault, fF- Fournier borehole, fUG-Usine à gaz borehole, S2- Ambrosis borehole, S3- Canton rouge borehole. 1- Mésozoïque substratum, 2- Rupelian formations, 3- Chattian formations, 4- Etoile breccias, 5-southern limit of the Jarret basin, 6- Pleistocene travertines, 7- the Sea, 8- faults, 9-reverse faults, 10-dip of bedding, 11- structural features, 12-stream, 13-boreholes, 14-émissaire n°l, 15- highways, 16-mounts, 17-cities.
***Figura 3.*** *Esquema structural de las cuencas de Marsella-Aubagne.*

basins are crossed by the Huveaune River, while the northern Jarret basin is drained by the Jarret River (Fig. 3). Each basin exposes its own stratigraphic, sedimentologic and structural characteristics. For example, the main structural features of the southern and eastern basins (Aubagne and Prado) trend SSW-NNE to SW-NE, while those in the northern basin trend WSW-ENE. Figure 3 illustrates that the Allauch horst separating the Prado basin from the Jarret basin, is partly covered by the Oligocene sediments.

### *Lithostratigraphic successions for each basin*

Owing to the rapid facies variability of sediments deposited in a continental context, three different stratigraphic scales have been established, which is one for each basin. Each local scale includes a group with several formations and members. Thus, the groups of Jarret, Prado and Aubagne basins are delineated in Figure 4. Given the continental character of these deposits, it would not have been reliable to use the previously unique global scale (Nury, 1988).

The Jarret group includes eight formations which are from base to top:

The Striatelles of the Poncet formation (Early Rupelian, 20 m) is composed of grey and yellow limestone containing fossils of Striatelles that are interbedded with breccias with rocks from the basement.

The Marinier formation (Early Rupelian, 50 to 200 m) comprises three members which are from base to top: 1) Lower member: composed of laminated or slabbed limestone, 2) Middle member: built up of a succession of breccias, argilites and limestones (80 to 100 m), 3) Upper member: made of white limestone in thick beds (10 to 50 cm) with silex kidneys and thin silicic beds.

The Estaque-Port formation (Late Rupelian to Chattian, 100 m) crops out at the southern flank of the Estaque fault (FE). It is composed of white limestone in beds of 20 to 80 cm, resulting in a total thickness of 100 m. These rocks are capped by the St André-St-Henri argillites, although Nury (1988) supports a local interfingering with *the* underlying limestone.

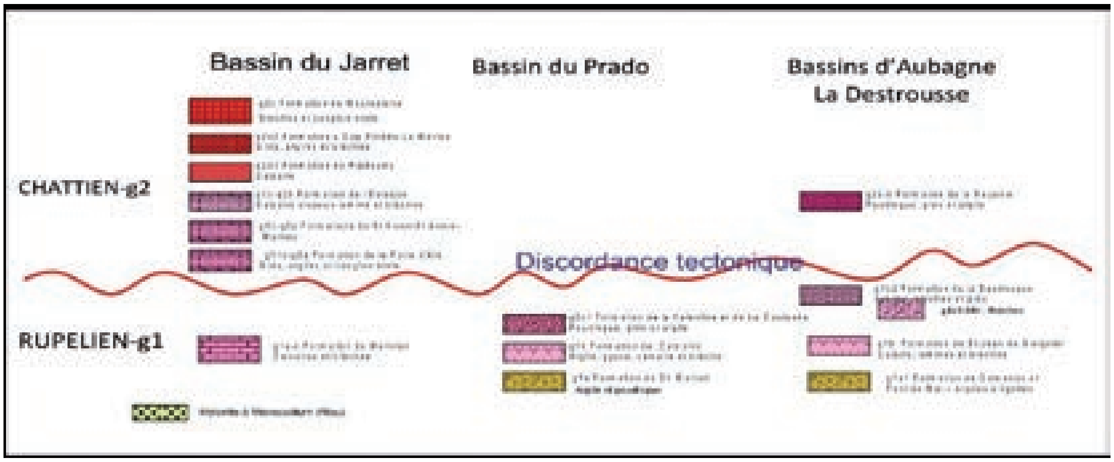


**Figure 4.** Lithostratigraphic successions in the Oligocene basins.
***Figura 4.*** *Sucesiones litoestratigráficas en las cuencas oligocenas.*

The St. André-St. Henri formation (Late Rupelian to Early Chattian) corresponds to the St. André-St. Henri argillites, which are used to make tiles. The most common levels are named “grise des fonds”, “rouge des fonds”, “bonne grise”, “Delavoir”, and “Barthelemy-Fenouil” from base to top.

The Porte d’Aix formation (Early to Middle Chattian?) is inferred to be mainly of fluvial origin. Samples collected close to the Porte d’Aix contained *Chara microcera* indicating a non-specific Late Rupelian to Late Chattian age (Feist *et al.,*1994). But pollen grains from the underlying Colbert interurban train station indicate a Late Rupelian or an Early Chattian age (zone II, Châteauneuf and Nury, 1995) postponed which should be correlated to the lower part of the following Cap Pinède–Merlan formation.

The classic assemblage of the Cap Pinède-Merlan formation (Early to Late Chattian) consists of thin layers (2 to 4 m) of conglomerates (poudingues), yellow sandstone and red or yellow marls. They are interbedded with levels of lignite that are some metres thick. This trilogy is vertically duplicated, and thus, reaches up to 500 m in thickness in the Fournier well (St Mauront area).

The Piédautry formation (Middle to Late Chattien) comprises a succession of yellow marls, limestone and marly limestone and is located at the eastern part of the Jarret basin.

The Mourepiane formation (Late Chattian or younger) is characterised by a succession of breccias and conglomerates exhibiting a specific orange colour (salmon colour). The lack of Palaeozoic pebbles distinguishes this formation from the Cap Pinède-Merlan formation. Unfortunately, no fossils have been found in these rocks. We believe that these Mourepiane breccias could be linked to the “Etoile brecchias” that previously have been ascribed to the Pleistocene (Guieu *et al.,* 1969).

However, such a conventional succession should be questioned, taking into consideration the continental environment of the deposition. For example, the lateral change of the Cap Pinede-Merlan into the Piedautry marls was supported by Denizot (1930) and the Mordeau breccias (part of the Etoile breccias) may be intricated with the Piedrautry marls (Nury, 1988). In another location, Denizot (1920) supports the interfingering of the “Etoile breccias” with the Cap Pinède-Merlan poudingues. Thus, the southern conglomerates and northern breccias may represent the edge of coarse clastic deposits; whereas the Piedrautry marls are interpreted to be fine-grained clastic deposits of the inner basin. This hypothesis is consistent with the sedimentary model of sedimentation in a “graben” like structure.

At the current stage of knowledge only seismic studies and associated boreholes would be able to validate our hypothesis.

The Prado group contains three formations which are from base to top:

The Saint-Marcel formation (Early Rupelian), which can be well studied in the St. Marcel quarry (eastern part of Marseille). The three members that have been identified are from base to top:

The member in the XXVI Centenary Park: This member is about 200 m thick and can easily be studied in the Prado tunnel underneath the park. It is composed of grey, green or brown argillites with lenses of conglomerates. Towards the base, several lignite beds of 0.50 to 1 m thickness can be observed. Fossils of Charophyts (*Nitellopsis (Tectrochara) meriani, Lychnothamnus pinguis and Chara sp.*) indicate an Early Rupelian age. In addition, sandstone samples from Mazargues display *Nystia Chastelli Plicata* and *Brotia melanoides* (gastropods) and *Leguminocythereis verricula -scrobiculata* (ostracods) indicating a Latest Ludian or an Early Rupelian age.

The St. Marcel lower member (200 m) is made of grey or blue marls with lenses of conglomerates. Beds of lignite or gypsum can also be found.

The St. Marcel upper member comprises marls and orange sandstone associated to lenses of conglomerates. The general dipping of the layers is between 35° and 40°.

The Camoins formation (Early to Middle Rupelian) is mostly known from boreholes dug in the Camoin area. They went through laminated limestone, grey marls and gypsum levels associated to sandstone and breccias.

The Valentine formation. (Late Rupelian to Early Chattian) includes two members, which are distinguished by their colour: a red to orange lower member and an upper yellow member. They are made of sandy argillites, sandstone and lenses of conglomerates with Palaeozoic pebbles (quartzites, lydites and quartzphyllites). Unfortunately, no consistent fossils have been found except gastropod shells and vegetal remains.

In this group, the dip of bedding varies between 0 to 60°, but the mean dip is between 35° to 50°.

The Aubagne group includes six formations, which are from base to top:

The Gémenos formation. (Early Rupelian) is made up of more than 45 m of yellow and bluish grey argillites, interbedded with three metre-size beds of lignite and thin limestone layers.

The Font de Mai formation (Early Rupelian?) consists of red argillites with lenses of conglomerates which extend from “Font de Mai” to “La Source” on the southern flank of the Allauch-Garlaban massif. Based on drill-hole data, the thickness of these sediments reaches more than 60 m.

The type locality of the St Jean de Garguier formation (Middle Rupelien) is Saint-Jean de Garguier, north of Gémenos. This formation is made of limestone with plant fossils, laminated limestone, gypsum and breccias. In past times, a gypsum mine was operating here.

The La Gastaude formation (Late Rupelian) is, like the Valentine formation of the Prado group, subdivided into two members. A lower member with red color and an upper member with yellow colour. The age of the deposits is still unknown, but zircons extracted from the upper member display an age of 28.74 ± 0.54 Ma (Villeneuve *et al.,* 2013), and thus define the maximum age of sedimentation.

The La Destrousse formation (Late Rupelian) is characterised by three units that are similar to the following three members, which are from base to top Nury (1988):1) - Lower member: composed of grey or brown argillite, laminated limestone and brown argillite on top. 2) - Middle member: made of red argillite with lenses of conglomerates (pudding stone) and white or green limestone with Charophyts stems. 3) - Upper member: consisting of breccias and conglomerates with Palaeozoic pebbles (quartzites, lydites, quartzphyllites, etc.).

The La Royante formation (Early or Middle Chattian?) is made of conglomerates, sandstone and argillites. No fossils have yet been found in this formation. However, inherited zircons extracted from the Bonne Jeanne microconglomerates yield a 27.40 ± 0.51 Ma age that pre-dates this formation. In contrast to other formations in the group, the La Royante formation is flat and undeformed. This formation is separated on land from the Gastaude formation by a normal fault.

To sum up, the Oligocene stratigraphy is characterized by many changes that can easily be noticed by considering three local scales. However, possible correlations between them are presented in Figure 4.

### *Paleontological and chronostratigraphical data*

Of more than 60 new analyses on Oligocene samples, only three delivered relevant fossils. These three samples are:

V288, argillites from the XXVIeme centenaire tunnel, which contain *Nitellopsis (Tectrochara) meriani, Lychnothamnuspinguis et Chara sp.,*(Riveline, personal communication) thus indicating an Early Rupelian age.

V495, sandstones from Mazargues which display *Nystia Chastelli Plicata* and *Brotia melanoides* (gastropods) and *Leguminocythereis verricula -scrobiculata* (ostracod) indicating a Latest Ludian or an Early Rupelian age (Châteauneuf and Cavelier, personal communication)

V295, argillites from the Porte d'Aix formation,which contain *Chara microcera* indicating a Late Rupelian to Chattian age. This is consistent with the age of pollen grains collected in the underlying argillites of the Colbert metropolitan station (Châteauneuf and Nury, 1995) which are typical for a Late Rupelian to Early Chattian age.

However, these data are valuable as they constraint the age of the basal units within the Prado and Jarret basins.

The compilation of the new data allows the presentation of a new chronostratigraphic chart (Table 1) that is based on six fossil groups instead of four fossil groups used in the previous one (Nury, 1988). Table 1 underlines two stratigraphic gaps: the first one is in the Late Rupelian and the second one in the Early Chattian. These gaps may be related to a lack of outcropping deposits or to a lack of relevant fossils.

### *Radiometric datings*

In addition to the fossil studies, radiometric dating on inherited zircon extracted from conglomerates or sandstone was done. Therefore, six samples from the Gastaude formation (V240b), from the La Royante formation (BJ1 and V269) and from the Cap Janet-Merlan formation (CH3, V181b and V230b) have been dated by measuring the U-Pb content of zircon. In order to decipher the Oligocene tectonic history of the basins, only zircons younger than 100 Ma will be taken into consideration in this paper.

U-Pb age determination and Th-U measurement via LA-ICP-MS. In order to avoid mixed U-Pb ages resulting from different late- to post magmatic or metamorphic influences, spots for isotope analyses were preferentially set on monophase growth patterns. U-Th-Pb isotopic analyses took place at the GeoPlasma Laboratory, Senckenberg Naturhistorische Sammlungen Dresden and were carried out via LA-ICP-MS (Laser Ablation with Inductively Coupled Plasma Mass Spectrometry) techniques. Therefore, a Thermo-Scientific Element 2 XR instrument coupled to a New Wave UP-193 Excimer Laser System was used (for data see Table 1). The mounts were put into a teardrop-shaped, low volume laser cell, produced by Ben Jähne (Dresden), for ablation. This facilitates sequential sampling of heterogeneous grains (e.g. growth zones) during time-resolved data acquisition. Single measurement

| STAGES | LOCAL SUBSTAGES | FORMATIONS | | BIOZONES | | | | | | OLIGOCENE TIME SCALES BERGGREN ET AL. 2005 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | LE ROUET | MARSEILLE AUBAGNE | GASTROPODS | MAMMALS | CHAROPHYTES J. RIVELINE | POLLEN AND SPORES J.J. CHATEAUNEUF | DINOFLAGELLATE CYSTS | OSTRACODS APOSTOLESCU ET AL.1999 REVISE (NURY) | |
| 23,3 Ma<br>CHATTIAN | LATE CHATTIAN | Cap des Nautes and Cap de la Vierge<br>Upper Rouet sandstones and conglomerates | Mourepianne | Potamides Lamarchii Wenzia ramondi Pomatias antiquus | MP30 | Chara notata | Megatherms and Avicennia pollen grains | Glaphyrocysta exuberans et laciniiformis | VI | O7 to O6 top (NP25) |
| | MIDDLE CHATTIAN | Lower Rouet sandstones and conglomerates | Cap janet and Pied d'Autry Collet-Redon Cap Pinede-Merlan Ported'Aix-V295-Royante | | | | Microtherms | Absence | | |
| | EARLY CHATTIAN | | Gap | | | | | | | |
| 28,1 Ma | | | Saint Henri_ Saint André L'Estaque port | Wenzia ramondi Potamides lamarchii and Tympanotonos labyrinthus | MP26<br>MP 25? | Lychnothamnus ungeri<br>Chara microcera? | Slowakipollis hippophaeoides | of | V | O5 (NP24) |
| | | | | | | | | | IV | O4-O5 (NP24) |
| | | | Gap | | | | | | | |
| RUPELIAN | Rupélien supérieur | | La /La Destrousse Valentine/La gastaude Les Camoins Peypin | P. lamarchii T. labyrimthus and last Melanoides touranei | (MP 24) (MP23) (MP 22) MP 21 | Lychnothamnus major | Boehlensipolis hohli and Slowakipollis hippophaeoides | Dinocysts<br>Wetzeliella gochtii | III | O3 (NP23) |
| | Rupélien inférieur | | Saint Marcel V288 V495 Saint Zacharie limestones and lignites | Brotia laurae and rare "Striatelles" | | | | | II | O2 (NP23) |
| 34 Ma | | | | "striatelles" layers (Melanoides) | | Lychnothamnus pinguis | | | I | O1 (NP21) |

**Caption (MP22) : Mammals zones proposed after corrélations of formations with those of nearest Provence basins**

**Table 1.** Chronostratigraphic chart of the Oligocene formations in the Marseille-Aubagne basins.
***Tabla 1.*** *Escala cronoestratigráfica de las formaciones oligocenas en las cuencas de Marsella-Aubagne.*

of one spot is composed of approximately 15 s background acquisition followed by 30 s data acquisition. With respect to grain structure and size, the chosen spot sizes ranged between 15 and 35 μm. Judgement of necessity for correction depended on whether the corrected $^{207}Pb/^{206}Pb$ 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. Finally, raw data were corrected for background signal, common-Pb, laser induced elemental fractionation, instrumental mass discrimination, depth- and time-dependant elemental fractionation of Pb/Th and Pb/U by use of an Excel® spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann Wolfgang Goethe-University Frankfurt, Frankfurt am Main, Germany). Th/U ratios were measured parallel to U-Pb determination with same combination of instruments. The given uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (~0.6 % and 0.5-1.0 % for the $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia diagrams (2σ error ellipses) and concordia ages (95 % confidence level) were produced by using Isoplot/Ex 2.49 (Ludwig, 2001). The program Age Display (Sircombe, 2004) was employed to generate frequency as well as relative probability plots. For zircons with ages older than 1 Ga, $^{207}Pb/^{206}Pb$ ages were taken for interpretation, the $^{206}Pb/^{238}U$ ages for younger grains. Further details on analytical protocol and data processing are reported in Gerdes and Zeh (2006).

## Results

The samples BJ1, CH3, V181b, V230b, V240 and V269 contained 37 zircon grains having apparent $^{206}Pb/^{238}U$ ages below 100 Ma, all of which were analysed with respect to their U-Th-Pb content. In total, 31 of the analysed grains yielded ages between 27 ± 1 and 35 ± 1 Ma with a concordance between 90 and 110 %. Only the latter data were used for interpretative purposes. The visualisation of primary magmatic events in the source areas of the sediments is given in binned frequency and probability density distribution plots (Fig. 5). Most of the grains show undisturbed concentric zoning related to magmatic crystallisation. Only eight grains displayed homogenisation or larger areas of re-crystallisation, which can be linked to metamorphic overprint (Corfu *et al.,* 2003). These observations correlate very well with the obtained Th/U ratios, which are in between 0.02 and 0.90, while values from 0.02 to 0.12 could only be found in the eight metamorphic grains. Values lower than 0.1 are also supposed to be a result of metamorphism (Wang *et al.,* 2011). Concordant grains display ages from 27 ± 1 to 35 ± 1 Ma, while main age populations cluster around 27.30, and 32 Ma. The 16 youngest zircons give a calculated concordia age at 27.41 ± 0.22 Ma (Fig. 5, Table 2).

## Interpretations

Apart from those zircons reflecting the Archaean, Proterozoic, Pan-African and Variscan orogens that commonly occur in the Corso-Sarde block, we found inherited zircons which display mainly Oligocene ages (37 to 25 Ma). We suggest that these zircons

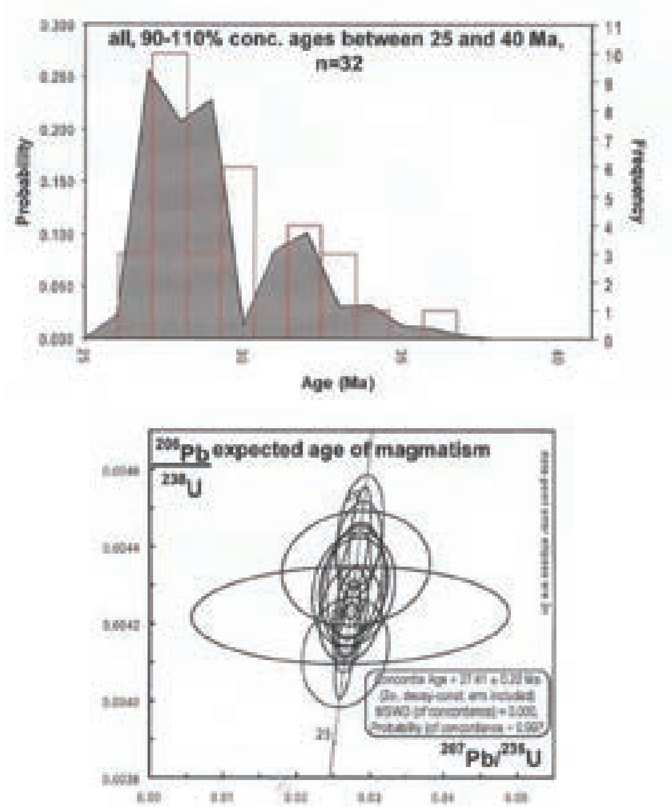


**Figure 5.** Binned probability density plots of all zircons younger than 100 Ma measured for U-Pb age determination yielding concordance levels of between 90 and 110 % from the Oligocene sandstones.
***Figura 5.*** *Representaciones de desidad de probabilidad agrupada para todos los circones de edad menor a 100 Ma datados por U-Pb dando niveles de concordancia entre el 90 y el 110% de las areniscas oligocenas.*

| Number | $^{207}Pb$ (cps) | U[a] (ppm) | Pb[a] (ppm) | Th[c]/U | $^{206}Pb/^{204}Pb$ | $^{206}Pb^{e}/^{238}U$ | 2 σ % | $^{207}Pb^{e}/^{235}U$ | 2 σ % | $^{207}Pb^{e}/^{206}Pb$ | 2 σ % | rho | $^{206}Pb/^{238}U$ | 2 σ (Ma) | $^{207}Pb/^{235}U$ | 2 σ (Ma) | $^{207}Pb/^{206}Pb$ | 2 σ (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BJ1_a01 | 655792 | 15786 | 114 | 0,02 | 3032 | 0,00276 | 3,1 | 0,26121 | 4,1 | 0,68736 | 2,7 | 0,75 | 18 | 1 | 236 | 9 | 4705 | 39 |
| BJ1_b02 | 517 | 179 | 1 | 0,51 | 1129 | 0,00431 | 2,9 | 0,02769 | 11,3 | 0,04660 | 10,9 | 0,25 | 28 | 1 | 28 | 3 | 29 | 262 |
| BJ1_b31 | 541 | 206 | 1 | 0,58 | 1185 | 0,00422 | 2,4 | 0,02713 | 13,1 | 0,04658 | 12,8 | 0,19 | 27 | 1 | 27 | 4 | 28 | 307 |
| CH3_b17 | 522112 | 12099 | 114 | 0,02 | 2955 | 0,00368 | 2,7 | 0,30896 | 3,6 | 0,60951 | 2,4 | 0,74 | 24 | 1 | 273 | 9 | 4531 | 35 |
| CH3_b06 | 3551 | 976 | 5 | 0,09 | 3835 | 0,00413 | 2,5 | 0,02650 | 4,4 | 0,04656 | 3,6 | 0,57 | 27 | 1 | 27 | 1 | 27 | 86 |
| CH3_a03 | 2651 | 564 | 3 | 0,33 | 5795 | 0,00421 | 1,8 | 0,02700 | 4,9 | 0,04656 | 4,6 | 0,36 | 27 | 0 | 27 | 1 | 27 | 111 |
| CH3_a32 | 1580 | 436 | 2 | 0,35 | 3452 | 0,00423 | 2,3 | 0,02715 | 6,9 | 0,04659 | 6,5 | 0,33 | 27 | 1 | 27 | 2 | 28 | 156 |
| CH3_a44 | 1760 | 362 | 2 | 0,33 | 3878 | 0,00416 | 1,8 | 0,02672 | 5,9 | 0,04657 | 5,6 | 0,30 | 27 | 0 | 27 | 2 | 27 | 135 |
| CH3_a49 | 998 | 155 | 1 | 0,60 | 2160 | 0,00429 | 2,4 | 0,02758 | 14,2 | 0,04658 | 13,9 | 0,17 | 28 | 1 | 28 | 4 | 28 | 334 |
| CH3_a37 | 1363 | 354 | 2 | 0,24 | 2971 | 0,00452 | 2,0 | 0,02905 | 5,7 | 0,04662 | 5,3 | 0,36 | 29 | 1 | 29 | 2 | 30 | 128 |
| CH3_a41 | 2699 | 594 | 3 | 0,54 | 5897 | 0,00455 | 1,8 | 0,02924 | 5,4 | 0,04663 | 5,1 | 0,33 | 29 | 1 | 29 | 2 | 30 | 122 |
| CH3_a08 | 910 | 188 | 1 | 0,51 | 2005 | 0,00486 | 1,7 | 0,03129 | 10,1 | 0,04667 | 9,9 | 0,17 | 31 | 1 | 31 | 3 | 32 | 238 |
| CH3_b27 | 1689 | 247 | 1 | 0,51 | 246 | 0,00483 | 3,5 | 0,03108 | 48,6 | 0,04664 | 48,5 | 0,07 | 31 | 1 | 31 | 15 | 31 | 1162 |
| CH3_b25 | 779 | 195 | 1 | 0,12 | 1709 | 0,00498 | 2,5 | 0,03204 | 16,2 | 0,04667 | 16,0 | 0,16 | 32 | 1 | 32 | 5 | 32 | 383 |
| V240_b11 | 789 | 147 | 1 | 0,90 | 1724 | 0,00441 | 2,1 | 0,02830 | 9,0 | 0,04659 | 8,7 | 0,23 | 28 | 1 | 28 | 3 | 28 | 209 |
| V240_b42 | 583 | 113 | 1 | 0,53 | 693 | 0,00430 | 3,0 | 0,02759 | 13,2 | 0,04657 | 12,8 | 0,22 | 28 | 1 | 28 | 4 | 27 | 308 |
| V240_b12 | 2209 | 400 | 2 | 0,41 | 4828 | 0,00453 | 2,3 | 0,02911 | 4,0 | 0,04661 | 3,3 | 0,57 | 29 | 1 | 29 | 1 | 29 | 79 |
| V240_c04 | 7724 | 1615 | 10 | 0,08 | 16938 | 0,00456 | 1,8 | 0,02928 | 2,8 | 0,04661 | 2,2 | 0,65 | 29 | 1 | 29 | 1 | 30 | 52 |
| V240_b23 | 945 | 158 | 1 | 0,43 | 2058 | 0,00490 | 2,0 | 0,03156 | 8,2 | 0,04667 | 7,9 | 0,25 | 32 | 1 | 32 | 3 | 33 | 190 |
| V269_b42 | 472 | 114 | 0 | 0,83 | 1005 | 0,00412 | 2,8 | 0,02647 | 18,3 | 0,04657 | 18,1 | 0,16 | 27 | 1 | 27 | 5 | 27 | 434 |
| V269_b36 | 1566 | 520 | 3 | 0,74 | 3410 | 0,00431 | 2,4 | 0,02772 | 6,6 | 0,04659 | 6,2 | 0,36 | 28 | 1 | 28 | 2 | 28 | 149 |
| V269_b25 | 1438 | 486 | 3 | 0,36 | 3610 | 0,00488 | 2,0 | 0,03137 | 20,6 | 0,04666 | 20,6 | 0,10 | 31 | 1 | 31 | 6 | 32 | 493 |
| V269_c33 | 587 | 166 | 1 | 0,84 | 1245 | 0,00509 | 2,5 | 0,03278 | 15,0 | 0,04671 | 14,8 | 0,17 | 33 | 1 | 33 | 5 | 34 | 355 |
| V269_c34 | 293687 | 7064 | 92 | 0,04 | 5248 | 0,00582 | 21,1 | 0,21775 | 25,2 | 0,27128 | 13,8 | 0,84 | 37 | 8 | 200 | 47 | 3313 | 217 |
| V269_c12 | 244308 | 5727 | 83 | 0,04 | 10643 | 0,00735 | 62,2 | 0,13685 | 65,5 | 0,13499 | 20,7 | 0,95 | 47 | 29 | 130 | 83 | 2164 | 361 |
| V269_b10 | 168327 | 684 | 41 | 0,22 | 3725 | 0,01166 | 53,5 | 0,38806 | 80,0 | 0,24140 | 59,5 | 0,67 | 75 | 40 | 333 | 257 | 3129 | 945 |
| V230b_b35 | 1947 | 255 | 2 | 0,65 | 208 | 0,00422 | 2,5 | 0,02710 | 65,5 | 0,04656 | 65,5 | 0,04 | 27 | 1 | 27 | 18 | 27 | 1570 |
| V230b_a38 | 817 | 198 | 1 | 0,57 | 1790 | 0,00443 | 3,0 | 0,02844 | 9,4 | 0,04659 | 8,9 | 0,32 | 28 | 1 | 28 | 3 | 28 | 213 |
| V230b_a46 | 3190 | 466 | 3 | 0,11 | 1185 | 0,00429 | 2,8 | 0,02754 | 16,9 | 0,04658 | 16,6 | 0,17 | 28 | 1 | 28 | 5 | 28 | 398 |
| V230b_b25 | 2515 | 760 | 5 | 0,12 | 5497 | 0,00442 | 2,5 | 0,02839 | 4,5 | 0,04659 | 3,7 | 0,56 | 28 | 1 | 28 | 1 | 28 | 89 |
| V230b_a03 | 2093 | 450 | 2 | 0,33 | 4566 | 0,00452 | 2,0 | 0,02902 | 6,0 | 0,04662 | 5,7 | 0,33 | 29 | 1 | 29 | 2 | 30 | 137 |
| V230b_a30 | 2017 | 546 | 3 | 0,29 | 4427 | 0,00456 | 2,4 | 0,02930 | 4,7 | 0,04661 | 4,0 | 0,52 | 29 | 1 | 29 | 1 | 29 | 96 |
| V230b_a45 | 533 | 71 | 0 | 0,66 | 95 | 0,00549 | 5,5 | 0,03535 | 19,1 | 0,04672 | 18,3 | 0,29 | 35 | 2 | 35 | 7 | 35 | 438 |
| V230b_a09 | 3358 | 162 | 2 | 0,93 | 201 | 0,00652 | 5,5 | 0,15964 | 12,2 | 0,17770 | 10,8 | 0,45 | 42 | 2 | 150 | 17 | 2631 | 180 |
| V181b_a24 | 471 | 134 | 1 | 0,88 | 1050 | 0,00498 | 2,1 | 0,03202 | 19,4 | 0,04665 | 19,3 | 0,11 | 32 | 1 | 32 | 6 | 32 | 463 |
| V181b_a21 | 1707 | 303 | 2 | 0,35 | 1109 | 0,00524 | 2,0 | 0,03379 | 6,5 | 0,04672 | 6,2 | 0,30 | 34 | 1 | 34 | 2 | 35 | 149 |
| V181b_a25 | 408 | 88 | 0 | 0,35 | 814 | 0,00434 | 2,8 | 0,02790 | 29,8 | 0,04659 | 29,7 | 0,09 | 28 | 1 | 28 | 8 | 28 | 711 |

[a] within-run background-corrected mean $^{207}Pb$ signal in counts per second

[b] U and Pb content and Th/U ratio were calculated relative to GJ-1 and are accurate to approximately 10%.

[c] corrected for background, mass bias, laser induced U-Pb fractionation and common Pb (if detectable, see analytical method) using Stacey & Kramers (1975) model Pb composition. $^{207}Pb/^{235}U$ calculated using $^{207}Pb/^{206}Pb/(^{238}U/^{206}Pb \times 1/137.88)$. Errors are propagated by quadratic addition of within-run errors (2SE) and the reproducibility of GJ-1 (2SD).

[d] Rho is the error correlation defined as $err^{206}Pb/^{238}U/err^{207}Pb/^{235}U$.

**Table 2.** Radiometric data of all zircons younger than 100 Ma from the sediments of the Marseille-Aubagne basins.
***Tabla 2.*** *Datos radiometricos para todos los circones de edad inferior a los 100 Ma procedentes de los sedimentos de las cuencas Marsella-Aubagne.*

| **ICP-MS** | Finnigan Element 2 XR |
|---|---|
| Forward Power | 1390 W |
| Gas flow rate | 15.0 l min$^{-1}$ (plasma)<br>1.07 l min$^{-1}$ (aux) |
| Scan mode | E-scan |
| Scanned masses | 202, 204, 206, 207, 208, 232, 235, 238 |
| Mass resolution | 300 |
| Dead time | 18 ns |
| Oxide $UO^+/U^+$ | < 1% |
| Dwell time | 4 ms |
| Settling time | ≤ 1 ms/amu |
| Number of scans | 1500 |
| Background | 15 s |
| Ablation time | 30 s |
| Integration time | 1.4 s (=25 scans) |

| **Laser system** | UP193 New Wave<br>193 nm, excimer |
|---|---|
| Nominal spot diameter | 25-35 µm (unknown)<br>35 µm (standard) |
| Carrier gas | 0.25 l min$^{-1}$ He<br>1.1 l min$^{-1}$ Ar |
| Laser settings | 10 Hz, 55% LP |
| Drill speed (DS) /<br>Raster scan speed (RSS) | ~ 0.5 µm/s (DS) |
| Cell volume | c. 3 cm$^3$ |
| Sensitivity | 6 x 10$^6$ counts/pg U |

**Table 3.** Settings for the instruments used in the geochronological Laboratory (GeoPlasmaLab Dresden) of the Senckenberg Naturhistorische Sammlungen Dresden, (Excimer Laser, new wave, UP 193) and (ICP-MS, Thermo Fisher, Element 2 XR).
***Tabla 3****. Especificaciones de los instrumentos utilizados en el laboratorio de geocronología.*

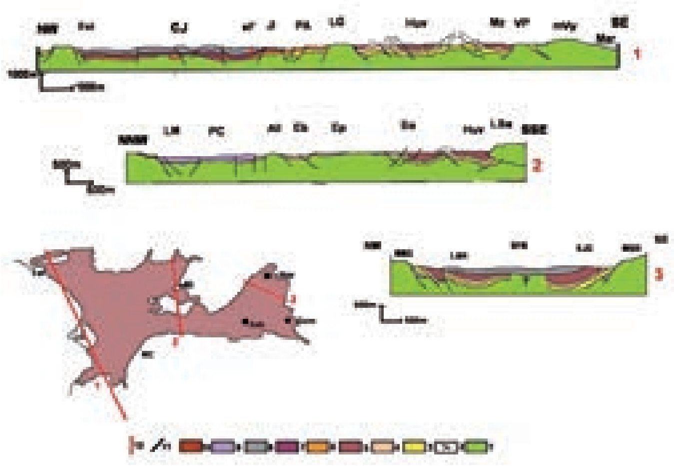

**Figure 6.** Geological cross-sections of the Oligocene Marseille-Aubagne basins. 1- Marinier to massif de Marseilleveyre cross-section, 2- Mordeau to la Barasse cross-section, 3-La Penne sur Huveaune cross-section, 4- Lascours to St-Jean de Garguier cross-section. 1- Mourepiane formation (=Etoile breccias), 2- Piedautry formation, 3- Cap-Janet Merlan and La Royante formations, 4- St André- St Henri formation, 5- Porte d'Aix formation and l'Estaque limestones, 6- La Valentine and La Gastaude formations, 7- les Camoins formation, 8- Marinier and St-Marcel formations, 9-Slope breccias, 10- Mesozoic basement, 11- faults, 12- Fournier borehole.
***Figura 6****. Cortes geológicos de las cuencas oligocenas de Marsella-Aubagne.*

are derived from the volcanic rocks associated to the "Western European rift" and the opening of the Western Mediterranean sea.

These youngest zircons show two significant peaks (Fig. 5): the first one around 32 to 33 Ma (Western European rift) and the second one around 27 to 29 Ma (Western Mediterranean rifting). These zircons do not give us any pertinent information on the depositional age of the sediments. Nevertheless, they define the maximum age for the deposition of each sample, which cannot be older than the youngest inherited zircons.

### *Tectonics*

The geological cross-sections presented in Figure 6 show that folds are more important in the Prado and Aubagne basins than in the Jarret basin. This is consistent with the widespread occurrence of undeformed Chattian sediments covering large areas of the Jarret basin.

Cross-section 3 is located in the Aubagne basin and shows a tectonic unconformity between the overlying Chattian La Royante formation and the underlying formations. This unconformity is related to the discrepancy between the lower deformed formations and the almost flat upper formations. The folding of the lower formations is assumed to be linked to a compressional tectonic event which has most likely taken place by the middle Oligocene (Villeneuve *et al.,* 2013).

Cross-section 2 shows the thrusting of the Calanque massif (Mesozoic) over the Prado basin

(Cenozoic). This thrust was already evidenced along the Barasse stream by Denizot (1952). In this place, the underthrusted formations belong to the Rupelian St. Marcel and Valentine formations. Thus, this thrust is thought to be coeval with the intra-Oligocene compressional tectonic event.

On the other hand, Hippolyte *et al.* (1990 and 1993) gave evidence for five tectonic events related to an extensive regime: two in the Rupelian period and three in the Chattian period. During the Rupelian the extensive trends were directed NW-SE, while in the Chattian they were successively oriented NE-SW, then NNE-SSW and finally NNW-SSE. According to this, the periods of the single extensive events are related to five different sedimentary cycles. Thus, we are setting our compressive event between the second and the third extensive period of Hippolyte *et al.* (1990 and 1993). Taking into consideration the data published by Villeneuve *et al.* (2013), this compressive event is inferred to be younger than 28.7 Ma. Hence, the limit is likely to be contemporary of the transition from Rupelian to Chattian.

### *Sedimentology*

A sedimentary model has been tested for these basins. It is able to provide a coherent explanation of the Oligocene deposits despite the paucity of outcrops. The deposits are related to a continental environment dominated by lakes and rivers.

Owing to the field relations, the most important rivers should have been on the southern side and the lacustric areas were mainly located on the northern side of the basins. Thus, the conglomerates which come from the southern flank get coarser to the south. On the other side the sedimentary environment of the Mordeau breccias (without fluviatile evidences) suggests a deposition in a shallow water context consistent with a Piedrautry lake. This hypothesis is enhanced by the location of the basal “Mordeau breccias” (part of the “Etoile” breccias) which crop out 30 m underneath a contact level between the Piedrautry marls and the upper part of the Mordeau breccias. However, further studies are needed to test this hypothesis.

The model proposes a “graben like structure” infilled during its extensional regime, at least for the lower part of the “Etoile breccias”. The best modern analog is a mountainous lake, such as the Genève or Annecy lakes fed by alpine rivers. However, taking into consideration a nearly coeval time between the tectonic folding of the Gastaude formation and the deposition of the “Porte d’Aix” formation, a foreland basin model for the Jarret basin is suggested.

With respect to the depositional environment and fossils, four biotopes have been considered: three in the continental environment (land, fresh water and brackish water) and one shallow marine environment that is only known at Carry le Rouet (out of the 1:50,000 geological map) and attributed to the end of the Oligocene time. The terrestrial environment exhibits numerous remains of vertebrates, mollusks, Helicitae, Pomatiidae, Zonitidea, pollen spores and vegetation. Rivers or lakes set up a fresh water environment, displaying numerous gastropods, such as *Viviparus, Pseudamnicola*, Bithynies, Neritidae, limnees, and planorbes that reflect a very shallow water environment (0 to 5 m) with only a few pelecypods, *Sphaerium* and *Pisidium* indicating a deeper environment (5 to 10 m). Floral components are represented by pollen and spores, charophyts and algae. Ostracods and occasionally insects are also present, as well as fresh water fish and turtles. In the brackish water environment, mollusks are well represented by Potamidinae, Melaniidae, Hydrobiidae, Cyrenidae. They reflect the typical biocenosis of an estuary environment. The lack of Cardiidae argues against a saliniferous lagoon (Nury, 1987, 1988). Coelentérés Siphonophores Chondrophorides, *Discalioides* nov. gen. (Nel *et al.,* 1987) were collected. They indicate a connection to the sea. Ostracodes from shallow water (Dellenbach and Apostolescu, 2001) pollen and spores from littoral origin (Chateauneuf and Nury, 1995) and pollen from *Avicennia* and *Wetzeliella gochti dinocyst* are also consistent with a connection to the sea. The coastal environment of Carry le Rouet is certified by many authors and noticeably by Gaudant (1982). This coastal environment could become lagoonal due to marine regression.

### *Paleogeography and basin evolution*

Matching our observations with those of Hippolyte *et al.* (1993), we consider seven stages in the evolution of these basins: Stage 1 corresponds to the N 20° oriented grabens, noticeably the Prado basin, and the associated N 90° to N 100° faults

Stage II is attributed to N 45° to N 70° grabens observed in the “Marinier” area, north of l’Estaque, in the “Maurins” area, and subsurface in the Prado basin. These structures are linked to the N 125° extensive regime evidenced by Hippolyte *et al.* (1993) during the Early to Middle Rupelian.

Stage III is assumed to follow a low erosive period and is represented by the Camoin and St Jean de Garguier formations. There is a more erosive period reported from the Prado and Aubagne basins, indicated by the conglomerates and sandstone of the Valentine and Gastaude formations and mainly deposited in the northern part of these basins. This period is consistent with the N 105° extensive regime introduced by Hippolyte *et al.* (1993).

Stage IV is supposed to have been taken place at the end of the Rupelian time, when the entire sedimentary successions were deformed. The variability of the directions of fold axes is a consequence of equatorial folds, reworked by a N-S trending direction of secondary folds. The migration of depositional-centers to the north could indicate a northward migration of the tectonic front line.

Stage V occurred most likely from the end of the Rupelian to the Early Chattian, during that period a NNW-SSE graben opened on the western part of the Jarret basin. The sedimentary environment is lacustric to the North (St-Andre / St -Henri quarries) and more detritic to the south (Joliette and Colbert areas).

Stage VI occured during the Chattian when the central SSW-NNE trending gap of the Jarret basin was gradually widened. Sedimentation during the Late Chattian was inferred from fluvial deposits spreading from the southern continental margin, except for the Allauch zone where a basin was filled with the marls and limestone of Piedautry. We suggest a coeval deposition of parts of the "Etoile breccias" along the northern flank of the Jarret basin. It was probably during this period that new conglomerates were recurrently deposited in the Aubagne basin (La Royante formation).

Stage VII is characterised by decreasing southern continental sedimentary input, but increasingly influenced by the northern massifs which fed the Jarret basin. According to this, massive breccias representing the upper part of the "Etoile breccias" were deposited and formed the Mourepiane formation, provided by the Etoile and Nerthe massifs.

A compressive tectonic event has been recorded within the "Etoile breccias" (Hippolyte *et al.,* 1993) which could be correlated to the off-shore synclines (with Aquitanian in the core) evidenced by Oudet (2008) and Pantaine (2010). Unfortunately, no age can be assigned to this tectonic event.

## Comparisons and correlations with the adjacent basins

Two zones have to be noted because they provide additional information that enriches the mentioned observations (Nury, 1988). These zones are situated to the east and to the west of the area covered by the Marseille-Aubagne map (Fig. 1).

On both sides of the Marseille-Aubagne geological map (1:50 000) there are two basins very similar to those of Marseille-Aubagne (Nury, 1988): the St-Zacharie basin to the east and the Carry le Rouet basin to the west.

The St-Zacharie basin contains beds of lignite, limestone, marly limestone, red argilites, sandstone and conglomerates (poudingues). All these sediments belong to the Rupelian and were folded, which is very similar to the Aubagne and La Detrousse basins.

Located on the southern side of the Nerthe mountain range, the Carry le Rouet basin, Nury, Rey & Roux (1970) and recently Oudet (2008) have revised the stratigraphy and the sedimentology of this basin. They distinguished two main units:

A Lower red continental unit including both Lower and Upper Rouet formations which are respectively correlated to the Cap Janet and to the Mourepiane formations.

An Upper unit including the Cap des Nautes and Cap de la Vierge formations which display the first marine levels. "*Wenzia ramondi"* (gastropod) and a mammal assemblage belonging to Coderet zone have been found in these formations. These marine beds have yielded dinocysts, among others *Gl. exuberans* and *laciniiformis* have ranges limited to the top of Chattian stage in North Sea and areas of Germany. Nury, (1967) correlated this formation to the "Sable des Figons" (Aix-en-Provence basin) which displays

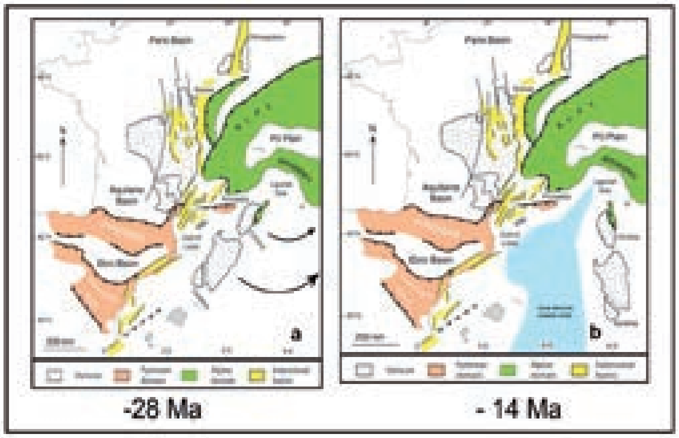


**Figure 7.** The main geological units in Western Europe, a) - Grabens related to the West European rift (yellow) and b) - The Western Mediterranean Sea in the Miocene (blue). Explanations have been done in the text. The southern Marseille Aubagne basins (Prado and Aubagne basins) are linked to the "West European rift system" meanwhile the northern basin (Jarret basin) is linked to an aborted branch of the Western Mediterranean Sea opening.
***Figura 7****. Las unidades geológicas principañes de Europa accidental.*

a characteristic alpine mineral association (glaucophane, actinolite, epidotic, green hornblende). Then, the Miocene sea passed the Nerthe massif and flooded the Aix basin.

## Discussion and interpretations

The evolution of the Marseille-Aubagne Oligocene basins is consistent with the coeval evolution history of the western part of Europe.

First of all (Fig. 7a), we suggest a similar orientation between the Prado and Aubagne basins and those of the West European rift including the Valencia (Spain), Ales, Limagne, Bresse, Alsace and North Sea grabens.

Secondly, the Chattian WSW-ENE structure of the Jarret basin, is more consistent with the Western Mediterranean rifting which began around 28 Ma (synrift) and became oceanic (post rift) around 21 Ma together with the anticlockwise drifting of the Corso-Sarde block (Fig. 7b). The Jarret basin could be an aborted branch of the Western Mediterranean rift.

## Conclusions

Our knowledge of the Marseille-Aubagne Oligocene basins has been improved since the last studies of Nury (1988) and Hippolyte *et al.* (1993).

Three basins with different structures and evolution have been recognized. We suggest the establishment of a separate stratigraphic chart for each one. The chronostratigraphical chart has been completed with new fossil analysis and the implication of two new groups of fossils.

From the tectonic point of view we have evidenced a tectonic event that occurred at the Rupelian / Chattian limit.

The sedimentological approach has been improved by the implication of a graben with a single extensive regime. However, a foreland basin with a compressional component is possible for the early stage of the Chattian part of the Jarret basin.

The interpretation of the basins evolution has also been improved by the distinction of seven tectono-sedimentary stages, including a possible compressive stage supported by Villeneuve *et al.* (2013).

Therefore, the Marseille-Aubagne basins have been correlated to the main geodynamic European events: the Prado and Aubagne basins are linked to the “West European rift” which went through Western Europe, from Spain to the North Sea, whilst the upper part of the Jarret basin is correlated to the Western Mediterranean sea opening.

Despite these geological improvements, many matters have not yet been solved. Neither the thicknesses of the sedimentary successions, nor the structures of the basins are known. So far, no seismic profiles or deep boreholes (more than 150 m) exist, except the Fournier borehole (870 m) which was dug at the beginning of the 20th century.

Future studies should investigate the subsurface formations with respect to their importance for the entire overlying area and to increase our regional geodynamical knowledge.

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