Pre-Pliocene tectonostratigraphic framework of the Provence continental shelf (eastern Gulf of Lion, SE France)


To cite this version:


HAL Id: hal-01463727
https://hal-amu.archives-ouvertes.fr/hal-01463727
Submitted on 16 Feb 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Pre-Pliocene tectonostratigraphic framework of the Provence continental shelf (eastern Gulf of Lion, SE France)

FRANÇOIS FOURNIER1, AURÉLIE TASSY1, ISABELLE THINON2, PHILIPPE MÜNCH1, JEAN-JACQUES CORNÉE3, JEAN BORGOMANO1, PHILIPPE LEONIDE1, MARIE-ODILE BESLIER2, ARNAUD FOURNILLON1,7, CHRISTIAN GORINI3, POL GUENNOC2, JULIEN OUDET1, MARINA RABINEAU6, FRANÇOISE SAGE4 and RENAUD TOULLEC1,8

Mots-clés. – Géologie marine, Tectonostratigraphie, Stratigraphie sismique, Paléogéographie crétacée, Riftin oligo-miocène, Compression post-rift

Résumé. – Le prolongement en mer des formations et des structures provençales était jusqu'âlors largement inconnu. L'interprétation de profils de sismique-réflexion marine 2D et l'intégration de dragages et carottages du fond-marin ont permis d'apporter des éléments nouveaux concernant le cadre stratigraphique, structural et paléogéographique des dépôts anté-Messiniens du plateau continental de Provence. Sept unités sismiques post-jurassiques ont été identifiées sur les profils sismiques, cartographiées à travers le plateau continental et corrigées avec les séries affleurant à terre. Une épaissse unité apto-albienne (jusqu'à 2000 m) dont le dépôt est contrôlé par des failles E-W a été mise en évidence en mer. L'existence d'un bassin subsissant au Crétacé supérieur sur le plateau continental de Provence a été confirmée par la mise en évidence de profils sismiques, cartographiées à travers le plateau continental et corrigées avec les séries affleurant à terre. Une épaissse unité apto-albienne (jusqu'à 2000 m) dont le dépôt est contrôlé par des failles E-W a été mise en évidence en mer. L'existence d'un bassin subsissant au Crétacé supérieur sur le plateau continental de Provence a été confirmée par le développement d'une épaisse série de bassin (jusqu'à 1500 m) reposant en downlap sur l’Apto-Albien. Le socle métamorphique de l’écluse de Sicié et sa couverture sédimentaire peut être considéré comme une relique allochtone du « Massif Méridional » ayant alimenté le Bassin sud-provençal en éléments terrigènes au Crétacé supérieur. Dans la rade de Marseille, une épaisse unité syn-rift (Rupélien à Aquitanien) a été mise en évidence (>1000 m), structurée en une série de synformes en échelon d’axe E-W et affectée par des failles d’orientation dominante N040 à N060. Sur le flanc sud des synformes, la formation de plis d’axe N050 est associée à une déformation syn-sédimentaire. La formation des synformes en échelon d’axe E-W résulterait d’une réaction de décollement des failles N040 à N060 pendant une phase de compression N-S dont l’âge est compris entre le Burdigalien inférieur et moyen (18-20 Ma). Enfin, les dépôts post-rift sont affectés des déformations mineures (réactivation de failles et plis associés), le long d’un couloir d’orientation N160 à l’ouest de la baie de Marseille, attribuables à une phase de compression post-burdigalienn et anté-pliocène.

Key words. – Marine geology, Tectonostratigraphy, Seismic stratigraphy, Cretaceous paleogeography, Oligo-Miocene rifting, Post-rift compression.

Abstract. – The seaward extension of onshore formations and structures were previously almost unknown in Provence. The interpretation of 2D high-resolution marine seismic profiles together with the integration of sea-bottom rock samples provides new insights into the stratigraphic, structural and paleogeographic framework of pre-Messinian Salinity Crisis (MSC) deposits of the Provence continental shelf. Seven post-Jurassic seismically units have been identified on seismic profiles, mapped throughout the offshore Provence area and correlated with the onshore series. The studied marine surface and sub-surface database provided new insights into the mid and late Cretaceous paleogeography and structural framework as well as into the syn- and post-rift deformation in Provence. Thick (up to 2000 m) Aptian-Albian series whose deposition is controlled by E-W-trending faults are evidenced offshore. The occurrence and location of the Upper Cretaceous South-Provence basin is confirmed by the thick (up to 1500 m) basinal series downlapping the Aptian-Albian unit. This basin was fed in terrigenous sediments by a southern massif ("Massif Méridional") whose present-day relict is the Paleozoic basement and its sedimentary cover from the Sicié imbricate. In the bay of Marseille, thick syn-rift (Rupelian to Aquitanian) deposition occurred (>1000 m). During the rifting phase, syn-sedimentary deformations consist of dominant N040 to N060 sub-vertical faults with a normal component and N050 drag-synclines and anticlines. The syn-rift and early post-rift units (Rupelian to early Burdigalian) are deformed and form a set of E-W-trending en echelon folds that may result from sinistral strike-slip reactivation of N040 to N060 normal faults during a N-S compressive phase of early-to-mid Burdigalian age (18-20 Ma). Finally, minor fault reactivation and local folding affect post-rift deposits within a N160-trending corridor localized south of La Couronne, and could result from a later, post-Burdigalian and pre-Pliocene compressive phase.
INTRODUCTION

The Provence continental shelf is located at the transition between the Gulf of Lion margin and the Ligurian margin. The Gulf of Lion and Ligurian margins are two segments of the northern margin of the Liguro-Provençal basin which is interpreted as a back-arc basin that formed as a result of the counter-clockwise rotation of Corsica-Sardinia micro-plate during the Miocene [Rêhault et al., 1984; Gorini, 1993; Gueguen et al., 1998; Carminati et al., 1998a and 1998b; Gattacceca et al., 2007]. Few attention has been paid on the marine geology of this transitional area between Gulf of Lion and Ligurian margins, and very few published interpretations of seismic and core data are available [Leenhardt et al., 1969; Ducrot, 1967; Froget, 1967, 1971, 1972, 1974], in contrast to the Gulf of Lion margin [e.g. Gorini, 1993; Guennoc et al., 2000; Séranne, 1999; Lofi et al., 2003, 2005; Lofi and Berné 2008; Bache et al., 2010; Oudet et al., 2010; Moulin et al., 2015] and the Ligurian margin [e.g. Rollet, 1999; Rollet et al., 2002; Bigot-Cormier et al., 2004; Larroque et al., 2010; Sage et al., 2011]. The tectonic style of the Gulf of Lion margin differs significantly from that of the Ligurian margin since the latter was strongly influenced by post-rift tectonic inversion [Bigot-Cormier et al., 2004; Sage et al., 2011]. The occurrence of extensive oligo-miocene and plio-quaternary deposits on the Provence continental shelf [Oudet et al., 2010; Tassy et al., 2014] provides a good opportunity to evidence and characterize the syn-rift and post-rift deformation at the transition between the Gulf of Lion and Ligurian margins.

On the basis of an integrated seismic, rock sample and field study, the present work aims at 1) constructing a tectono-stratigraphic framework for the Provence continental shelf by defining and interpreting the main seismo-stratigraphic units and remarkable surfaces, 2) mapping and characterizing the main structural domains, 3) providing new insights into the Mesozoic and Cenozoic paleogeography of Provence, and 4) characterizing the syn-rift and post-rift deformation of the Provence margin.

GEODYNAMIC HISTORY OF PROVENCE

During the rifting of the Liguro-Piemontais domain (Middle Triassic to Late Jurassic), the Provence area was located on a NE-trending margin of the Alpine Tethys [e.g. Stampfl and Borel, 2002]. The extensional regime related to the opening of the Liguro-Piemontais ocean continued during the Early Cretaceous, thus resulting in the development of thick carbonate platform deposits in Provence [e.g. De Graciansky and Lemoine, 1988; Masse et al., 2009]. During the latest Barremian-earliest Aptian, the carbonate platforms drowned in southern Provence as a result of the development of a subsiding basin. During the mid-Cretaceous (Albian-Lower Cenomanian), the formation of the Durance high [Gignoux, 1925; Masse and Philip, 1976] resulted in the subaerial exposure of the Provence area and the development of a major regional unconformity. During the Cenomanian to the Santonian, a rather shallow (~200 m water-depth), east-west trending, narrow and elongated basin was formed (South Provence basin) in a transgressive regime that prevailed mainly during the Turonian-Coniacian [Floquet and Hennuy, 2003; Hennuy, 2003; Floquet et al., 2005, 2006; Reijmer et al., 2015]. The South Provence basin was bordered to the north by an extensive carbonate platform and to the south by an emerged crystalline massif [Philip, 1970; Hennuy, 2003].

At the end of the Cretaceous (late Santonian), the convergence between Europe and Iberia was initiated [e.g. Dercourt et al., 1986; Stampfl and Borel, 2002] and led to the development of the Pyrenean fold-and-thrust belt [e.g. Mattauer, 1968; Roure and Choukroune, 1998; Bestani et al., 2015]. In Provence, a thick continental succession (~1200 m at the depocentre of the Arc basin), of late Santonian to Lutetian age, deposited in a foreland setting [Leleu et al., 2009]. During the Late Eocene (Bartonian) a major phase of shortening occurred with north-verging fold and thrust development, overprinting the former structures [e.g. Lutaud, 1935; Guiue, 1968; Tempier, 1987; Lacombe and Jolivet, 2005].

During the latest Eocene and Early Oligocene, the E-W extension in the West-European platform led to the formation of the West-European rift system [Bergerat, 1987; Hippolyte et al., 1991; Ziegler, 1994; Séranne, 1999]. During the Late Oligocene a second extensional phase was initiated as a result of the opening of the Liguro-Provençal back-arc basin [Rehault et al., 1984; Hippolyte et al., 1993; Mauffret and Gorini, 1996; Mauffret et al., 2004; Gattacceca et al., 2007; Jolivet et al., 2015]. The opening of the Liguro-Provençal basin occurred in two steps: a syn-rift stage ( Chattian to early Burdigalian: 30-20.5 Ma) and a post-rift stage (early Burdigalian-Langhian: 20.5-15 Ma) with oceanic crust accretion and associated anticlockwise rotation of the Corsica-Sardinia continental block [e.g. Gattacceca et al., 2007]. Oligocene-Early Miocene extensional phases were responsible for the reactivation of NNE-trending faults such as the Aix-en-Provence fault system and for the formation of grabens such as the Marseille, Huveaune and Aix-en-Provence basins that are filled with thick (locally higher than 800 m), continental to shallow-marine successions [e.g. Nury, 1988; Hippolyte et al., 1993] (fig 1B).

In South-East France, the Alpine front propagated toward the SW, from the Late Oligocene to the Middle Miocene, thus leading to the reactivation of Pyrenean structures.

The onset of a compressive regime in Provence [Villeger, 1984; Villeger and Andrieux, 1987; Blès and Gros, 1991] is recorded from the Early Miocene, but its timing with regards to the end of the oceanic accretion in the Liguro-Provençal basin is still unclear. In northern Provence, the main Miocene Alpine fold-and-thrust deformation occurred during the Tortonian [Clauzon, 1984]. In southern Provence, evidences of post-rift deformation are scattered: 1) vertical movements (uplifts) that are recorded by sea-level markers such as Mio-cene marine abrasion surfaces [Champion et al., 2000] and Pliocene shelf breaks [Tassy, 2012], and 2) major regional faults that are considered to be active during post-oligoceen times such as the Salon Cavaillon fault [Moliex et al., 2011] and the Aix fault [Guignard et al., 2005] (fig 1B).

The morphology of the continental margins in the whole Mediterranean domain has been strongly affected by the so-called Messinian Salinity Crisis (MSC) that relates to a major and rapid sea-level drop that induced the development of a spectacular subaerial erosional surface (MES: Messinian Erosional Surface) [Hsu et al., 1973; Krijgsman et al., 1999; Manzi et al., 2013; Roveri et al., 2014 and references therein].

Bull. Soc. géol. Fr., 2016, n° 4-5
FIG. 1. – A) Bathymetric map of the Gulf of Lion, Provence and Ligurian margin (source: SHOM, IFREMER), B) Geological and structural setting of Provence, modified after Bestani et al. [2015], C) Location of the marine seismic profiles and cores and simplified onshore geological map.
PREVIOUS MARINE GEOLOGY STUDIES
OFFSHORE PROVENCE

In contrast to the neighbouring Gulf of Lion and Ligurian margins, few marine geology studies have focused on the Provence continental shelf and published seismic and core data are scarce. The first dredging of submarine outcrops from the Provence continental shelf has been carried out during the late 1940s around the Cassidaigne canyon [Bourcart, 1949] and yielded Palaeozoic metamorphic rocks within the canyon and Mesozoic dolomites and marls in the canyon’s head. New dredging surveys of the Provence continental shelf, performed by the Cousteau submarine saucer in the early 1960s, provided a significant pre-Pliocene submarine rock database from the Cassidaigne canyon and Blauquières shelf [Blanc and Blanc-Vernet, 1966; Blanc et al., 1967; Froget, 1971; Froget, 1974], Plio-Quaternary deposits of the Provence continental shelf have been studied with sedimentological [e.g. Blanc and Blanc-Vernet, 1966], diagenetical [Froget et al., 1972] and micropaleontological approaches [Blanc-Vernet, 1969]. A detailed geomorphologic study of the Provence continental slope has been conducted by Bourcart [1960] who identified and mapped the main submarine canyons. On the Provence continental shelf, later geomorphologic studies have evidenced the presence of extensive underwater notches at various water depths [Collina-Girard, 1992; 1997].

The first reflexion seismic survey on the Provence continental shelf has been performed in 1965 by the Oceanographic Museum of Monaco, using sparker seismic source, between the Planier islands and the Cassidaigne canyon. The results have been published by Leenhardt et al. [1969] who evidenced NE-SW antclines and synclines south of Riou island as well as various small-scale paleo-canyons incising the edge of the continental shelf and filled with sediment. Other sparker seismic profiles have been performed on the Banc des Blauquières, east of the Cassidaigne canyon and studied by Froget [1974] who evidenced the occurrence of a thick interval of deposits characterized by a layered seismic facies, crosscutting the Palaeozoic basement, that was interpreted as representing the sedimentary infill of a graben. During the 1980s, various oil exploration 3D seismic databases have been acquired in the Gulf of Lion. Most of the profiles are located in the continental slope or deep-water area, but some of them reach the continental shelf. Maps and paleogeographic reconstructions of the Oligo-Miocene and Plio-Quaternary deposits of the offshore Provence area have been performed from the stratigraphic interpretation of air-gun oil industry seismic profiles [Bache, 2008; Oudet, 2008; Oudet et al., 2010]. The recent acquisition of sparker and airgun seismic profiles offshore Provence (MARSOLIG-2008, CASSEIS-2009 and CASSEIS-2011 surveys) led to the revision of the interpretations by Froget [1974] regarding the Blauquières grabens. Tassy [2012] and Tassy et al. [2014] regarded such structures as steep flanked canyons formed during the Messinian and filled with Plio-Quaternary deposits.

DATABASE AND METHODS

The present study focuses on the Provence continental shelf located between Cap Couronne and Cap Sicié. The dataset used in this study includes marine seismic reflection 2D profiles (fig. 1), rock samples extracted from seabed and coastal outcrops. The present study is mainly based on newly acquired marine seismic data from 5 surveys performed on board the R/V TETHYS II vessel: MAST5913 (2007 and 2009), MARSOLIG (2008), CASSEIS (2009) and CASSEIS II (2011). The seismic profiles cover an area of approximately 1800 km² with a total survey length of 2740 km and an average profile spacing of 1 km. Seismic profiles consists of 255 high resolution (HR) and very high resolution (VHR) sections with a recording length ranging from 0.2 s to 2 s two-way-travel-time (TWTT). The seismic acquisition devices used for these seismic surveys are displayed in table I. In addition, older industrial and academic seismic surveys were integrated in this study [e.g. Gorini, 1993; Dos Reis, 2001; Lofi et al., 2003; Oudet et al., 2010]: GL80 (TOTAL), RMS4 (TOTAL), MARION (IFREMER), CALMAR-99 (IFREMER) and Carry (EOSYS). Paper seismic profiles from Leenhardt et al. [1969] were used for geological interpretations but were not integrated in the digital dataset.

<table>
<thead>
<tr>
<th>Seismic survey</th>
<th>year</th>
<th>Seismic source</th>
<th>Streamer</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMS5913-2007</td>
<td>2007</td>
<td>Air gun</td>
<td>Multitrace (6 traces)</td>
</tr>
<tr>
<td>MARSOLIG</td>
<td>2008</td>
<td>Sparker 1000J</td>
<td>Multitrace (6 traces)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sparker 50J</td>
<td>Montrace</td>
</tr>
<tr>
<td>CASSEIS</td>
<td>2009</td>
<td>Air gun</td>
<td>Multitrace (12 traces)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sparker 1000J</td>
<td>Multitrace (12 traces)</td>
</tr>
<tr>
<td>LMS5913-2009</td>
<td>2009</td>
<td>Air gun</td>
<td>Multitrace (12 traces)</td>
</tr>
<tr>
<td>CASSEIS II</td>
<td>2011</td>
<td>Sparker 1000J</td>
<td>Multitrace (12 traces)</td>
</tr>
</tbody>
</table>

The present study integrates descriptions of rock samples dredged from seabed and published by Froget [1967, 1972, and 1974] as well as newly acquired samples collected with the CNEXO-VILLE rock corer (BRGM) during the CASSEIS survey and published by Tassy et al. [2014]. The location and description of the seabed rock samples are summarized in table II.

The seismic interpretation is based on (1) the identification of major seismic horizons and major faults over the surveyed area and imaged by a maximum of cross-cutting lines and (2) the definition of seismic units that are bounded by extensively correlatable seismic reflectors or envelopes of seismic terminations and that are characterized by a given seismic facies. Seismic facies are defined by a set of seismic attributes such as reflector continuity, amplitude and frequency. The lack of offshore wells within the Provence continental shelf did not allow direct lithologic and chronostratigraphic calibration of the seismic strata to be performed. The chrono-stratigraphic interpretation of the seismic unconformities and units are based on 1) the interpretation of seismic facies in terms of lithology and small-scale (meter to decameter-scale) heterogeneity distribution, 2) the comparison between the seismic stratigraphic patterns evidenced from profiles offshore and the regional...
### Table II – Sea-bottom cores collected during the CASSEIS survey (2009)

<table>
<thead>
<tr>
<th>CORE NAME</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Water depth (m)</th>
<th>CORE DESCRIPTION</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR01</td>
<td>43°17.972</td>
<td>5°20.276</td>
<td>39.3</td>
<td>Clay with red algal crusts</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR01b</td>
<td>43°17.976</td>
<td>5°20.302</td>
<td>38.9</td>
<td>Clay with bioclasts and rock fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR02</td>
<td>43°18.112</td>
<td>5°20.158</td>
<td>48.4</td>
<td>Fine-grained sandstone</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR03</td>
<td>43°18.426</td>
<td>5°19.865</td>
<td>42.5</td>
<td>Argillaceous medium to coarse-grained sandstone</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR04b</td>
<td>43°18.432</td>
<td>5°19.986</td>
<td>45</td>
<td>Clay with bioclasts (Bryozone, Molluscs)</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR05</td>
<td>43°18.563</td>
<td>5°19.737</td>
<td>49</td>
<td>Clay with rock fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR05b</td>
<td>43°18.738</td>
<td>5°19.593</td>
<td>55</td>
<td>Ferruginized conglomerate</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR06</td>
<td>43°19.904</td>
<td>5°18.474</td>
<td>59.2</td>
<td>Pisolitic packstone with fresh-water gastropod molds (lacustrine limestone)</td>
<td>Oligocene</td>
</tr>
<tr>
<td>CR06b</td>
<td>43°19.885</td>
<td>5°18.493</td>
<td>59</td>
<td>Lacustrine limestone with gastropods</td>
<td>Oligocene</td>
</tr>
<tr>
<td>CR07</td>
<td>43°20.244</td>
<td>5°18.113</td>
<td>55.2</td>
<td>Medium-to-coarse-grained sandstone with angular quartz grain, calcite sparry cement</td>
<td>?</td>
</tr>
<tr>
<td>CR08</td>
<td>43°20.412</td>
<td>5°17.921</td>
<td>52.2</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR09</td>
<td>43°20.652</td>
<td>5°17.695</td>
<td>42.7</td>
<td>Argillaceous sand with shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR10</td>
<td>43°20.539</td>
<td>5°17.417</td>
<td>51.2</td>
<td>Argillaceous sand with pebbles</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR11</td>
<td>43°20.438</td>
<td>5°17.167</td>
<td>44.2</td>
<td>Argillaceous sand with shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR12</td>
<td>43°20.272</td>
<td>5°16.827</td>
<td>47.5</td>
<td>Argillaceous sand</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR13</td>
<td>43°20.095</td>
<td>5°16.413</td>
<td>52.5</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR14</td>
<td>43°19.962</td>
<td>5°16.138</td>
<td>50.5</td>
<td>Bioclastic sand, coralline crust, serpulites</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR14b</td>
<td>43°19.958</td>
<td>5°16.135</td>
<td>51</td>
<td>Marls and bioclastic sand, coralline crust, serpulites</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR15</td>
<td>43°19.926</td>
<td>5°16.061</td>
<td>51.5</td>
<td>Sandy Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR16</td>
<td>43°19.596</td>
<td>5°15.343</td>
<td>62</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR17</td>
<td>43°19.147</td>
<td>5°14.293</td>
<td>68</td>
<td>Packedstone with Foraminifera (miliolids), Scleractinian, Mollusks and Echinoderm</td>
<td>Oligo-Miocene</td>
</tr>
<tr>
<td>CR18</td>
<td>43°19.555</td>
<td>5°14.654</td>
<td>54.5</td>
<td>Carbonate mudstone with ostracods, gastropods, coated grains, circumgranular cracks (palustrine limestone)</td>
<td>Oligocene</td>
</tr>
<tr>
<td>CR19</td>
<td>43°19.333</td>
<td>5°14.315</td>
<td>60.7</td>
<td>Carbonate breccia with micritic elements (pedogenic breccia)</td>
<td>Oligocene</td>
</tr>
<tr>
<td>CR21</td>
<td>43°19.303</td>
<td>5°10.535</td>
<td>20.5</td>
<td>Conglomerate with rounded pebbles and sparry cements</td>
<td>Oligocene</td>
</tr>
<tr>
<td>CR22</td>
<td>43°19.111</td>
<td>5°10.989</td>
<td>40.7</td>
<td>Clay with rock fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR22b</td>
<td>43°19.109</td>
<td>5°10.989</td>
<td>40.9</td>
<td>Clay with shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR23</td>
<td>43°19.091</td>
<td>5°10.676</td>
<td>38</td>
<td>Clay with shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR24</td>
<td>43°19.079</td>
<td>5°9.938</td>
<td>25</td>
<td>Clay with red algae, Bryozoans, mollusks, serpulites</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR24b</td>
<td>43°19.078</td>
<td>5°9.951</td>
<td>31.7</td>
<td>red algal and oyster limestone</td>
<td>Oligo-Miocene</td>
</tr>
<tr>
<td>CR25</td>
<td>43°19.081</td>
<td>5°9.819</td>
<td>24.2</td>
<td>Recrystallized (calcitized) coral</td>
<td>Oligo-Miocene</td>
</tr>
<tr>
<td>CR26</td>
<td>43°18.692</td>
<td>5°9.492</td>
<td>29</td>
<td>Argillaceous bioclastic sand</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR26b</td>
<td>43°19.701</td>
<td>5°9.481</td>
<td>26.3</td>
<td>red algae and shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR27</td>
<td>43°18.684</td>
<td>5°8.363</td>
<td>27</td>
<td>red algae and shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR27b</td>
<td>43°18.701</td>
<td>5°7.956</td>
<td>33.5</td>
<td>red algae</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR28</td>
<td>43°18.704</td>
<td>5°7.477</td>
<td>40.7</td>
<td>Clay with shell fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR29</td>
<td>43°17.98</td>
<td>5°8.386</td>
<td>54.2</td>
<td>Fine-to-medium-grained sandstone with angular quartz grain, calcite sparry cement</td>
<td>?</td>
</tr>
<tr>
<td>CR29b</td>
<td>43°17.975</td>
<td>5°8.392</td>
<td>54.7</td>
<td>Medium-grained sandstone, limestone pebbles with perforations</td>
<td>?</td>
</tr>
<tr>
<td>CR30</td>
<td>43°17.968</td>
<td>5°8.848</td>
<td>57.5</td>
<td>Clay with mollusks and red algal fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR30b</td>
<td>43°17.971</td>
<td>5°8.815</td>
<td>53.7</td>
<td>Clay with Spondylus fragments</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR31</td>
<td>43°17.982</td>
<td>5°7.818</td>
<td>53</td>
<td>Medium-grained sandstone with angular quartz grain, calcite sparry cement, millidolites</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR32</td>
<td>43°17.996</td>
<td>5°6.658</td>
<td>62.7</td>
<td>Clay with algal mud</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR33</td>
<td>43°16.716</td>
<td>5°6.488</td>
<td>68.2</td>
<td>Medium-grained sandstone with angular quartz grain, calcite sparry cement, millidolites</td>
<td>?</td>
</tr>
<tr>
<td>CR34</td>
<td>43°17.888</td>
<td>5°11.029</td>
<td>54.5</td>
<td>algal sand</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR35</td>
<td>43°15.978</td>
<td>5°10.263</td>
<td>71.7</td>
<td>Quartzose calcarenite</td>
<td>?</td>
</tr>
<tr>
<td>CR36</td>
<td>43°15.552</td>
<td>5°9.496</td>
<td>73.5</td>
<td>Quartzose calcarenite with benthic forams</td>
<td>Oligo-Miocene</td>
</tr>
<tr>
<td>CR37</td>
<td>43°15.187</td>
<td>5°8.635</td>
<td>83.5</td>
<td>Quartzose calcarenite with benthic forams, echinoderms (echinoids, holothurians), leached/recrystallized mollusks</td>
<td>Oligo-Miocene</td>
</tr>
<tr>
<td>CR38</td>
<td>43°14.883</td>
<td>5°8.265</td>
<td>88.2</td>
<td>Fine-grained glauconitic sandstone with sparry cements</td>
<td>?</td>
</tr>
<tr>
<td>CR39</td>
<td>43°14.67</td>
<td>5°7.873</td>
<td>88.2</td>
<td>Fine-grained glauconitic sandstone with sparry cements</td>
<td>?</td>
</tr>
<tr>
<td>CR39b</td>
<td>43°14.668</td>
<td>5°7.869</td>
<td>88</td>
<td>Laminated silty clay with forams and strongly compacted sandstone with calcitic sparry cement</td>
<td>?</td>
</tr>
<tr>
<td>CR40</td>
<td>43°3.825</td>
<td>5°38.785</td>
<td>97</td>
<td>Phylloid</td>
<td>Paleozoic</td>
</tr>
<tr>
<td>CR41</td>
<td>43°3.325</td>
<td>5°38.277</td>
<td>93.2</td>
<td>Phylloid</td>
<td>Paleozoic</td>
</tr>
<tr>
<td>CR42</td>
<td>43°3.503</td>
<td>5°36.973</td>
<td>112</td>
<td>Phylloid</td>
<td>Paleozoic</td>
</tr>
<tr>
<td>CR43</td>
<td>43°3.883</td>
<td>5°35.213</td>
<td>127</td>
<td>Phylloid</td>
<td>Paleozoic</td>
</tr>
<tr>
<td>CR44</td>
<td>43°7.939</td>
<td>5°27.427</td>
<td>320</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR45</td>
<td>43°7.976</td>
<td>5°27.343</td>
<td>290</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR46</td>
<td>43°7.986</td>
<td>5°27.216</td>
<td>246</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR46b</td>
<td>43°8.034</td>
<td>5°26.987</td>
<td>148</td>
<td>Clay</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR48</td>
<td>43°7.983</td>
<td>5°31.352</td>
<td>293</td>
<td>Bioclastic sand</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR49b</td>
<td>43°7.343</td>
<td>5°31.352</td>
<td>123.2</td>
<td>Sparrtite limestone</td>
<td>?</td>
</tr>
<tr>
<td>CR50</td>
<td>43°8.067</td>
<td>5°32.433</td>
<td>40</td>
<td>Red algal sand</td>
<td>Quaternary</td>
</tr>
</tbody>
</table>
RESULTS

Definition of seismic units and chronostratigraphic interpretation

The interpretation of seismic profiles and the analysis of rock samples collected on the sea-bottom allowed seven

stratigraphic architecture onshore and 3) the dating of sea-bottom rock samples located on seismic profiles. Ages for sea-bottom rock samples have been determined by using benthic foraminiferal biostratigraphy or, when relevant microfossils were lacking, by lithologic and faciologic analogies with onshore regional outcrops.

TABLE II – follow

<table>
<thead>
<tr>
<th>CORE NAME</th>
<th>X</th>
<th>Y</th>
<th>Water depth</th>
<th>CORE DESCRIPTION</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR51</td>
<td>43°7’21”</td>
<td>5°32’104”</td>
<td>83,2</td>
<td>碳酸盐岩与红色生物灰岩，斜坡以及生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR52</td>
<td>43°8’194”</td>
<td>5°32’515”</td>
<td>37,2</td>
<td>碳酸盐岩与红色生物灰岩，斜坡以及生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR54</td>
<td>43°9’334”</td>
<td>5°32’424”</td>
<td>70</td>
<td>生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR55</td>
<td>43°9’83”</td>
<td>5°32’372”</td>
<td>75</td>
<td>生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR57</td>
<td>43°11’823”</td>
<td>5°31’752”</td>
<td>48</td>
<td>生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR57b</td>
<td>43°11’785”</td>
<td>5°31’762”</td>
<td>51</td>
<td>Echinoderm, Red algae and foraminifera</td>
<td>Cenomanian</td>
</tr>
<tr>
<td>CR58</td>
<td>43°11’82”</td>
<td>5°32’204”</td>
<td>48</td>
<td>砂岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR59</td>
<td>43°10’498”</td>
<td>5°32’331”</td>
<td>78</td>
<td>沙岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR59b</td>
<td>43°10’496”</td>
<td>5°32’297”</td>
<td>81</td>
<td>沙岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR60</td>
<td>43°10’485”</td>
<td>5°32’208”</td>
<td>80</td>
<td>硅质团状岩</td>
<td>Aptian-Albian</td>
</tr>
<tr>
<td>CR61</td>
<td>43°10’364”</td>
<td>5°31’889”</td>
<td>81</td>
<td>生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR62</td>
<td>43°10’377”</td>
<td>5°31’897”</td>
<td>80</td>
<td>碳酸盐岩与生物团状沉积</td>
<td>Cretaceous</td>
</tr>
<tr>
<td>CR63</td>
<td>43°10’351”</td>
<td>5°31’887”</td>
<td>82</td>
<td>生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR64</td>
<td>43°10’321”</td>
<td>5°31’664”</td>
<td>85</td>
<td>石英岩</td>
<td>?</td>
</tr>
<tr>
<td>CR65</td>
<td>43°10’125”</td>
<td>5°32’207”</td>
<td>79</td>
<td>浮游生物团状灰岩与层间岩质岩</td>
<td>Lower Cretaceous</td>
</tr>
<tr>
<td>CR65b</td>
<td>43°10’142”</td>
<td>5°32’177”</td>
<td>79</td>
<td>团状生物灰岩</td>
<td>?</td>
</tr>
<tr>
<td>CR66</td>
<td>43°10’214”</td>
<td>5°32’403”</td>
<td>69,6</td>
<td>生物灰岩与沙岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR70</td>
<td>43°9’846”</td>
<td>5°32’066”</td>
<td>85</td>
<td>生物灰岩沉积</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR71</td>
<td>43°9’256”</td>
<td>5°38’233”</td>
<td>68</td>
<td>石英砂与团状生物灰岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR72</td>
<td>43°9’109”</td>
<td>5°39’906”</td>
<td>43,2</td>
<td>石英砂与层间岩质岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR73</td>
<td>43°9’829”</td>
<td>5°39’620”</td>
<td>88</td>
<td>石英砂与层间岩质岩</td>
<td>Quaternary</td>
</tr>
<tr>
<td>CR74</td>
<td>43°9’289”</td>
<td>5°43’297”</td>
<td>59</td>
<td>团状碳酸盐与粒状碳酸盐</td>
<td>Pliocene?</td>
</tr>
<tr>
<td>CR74b</td>
<td>43°9’289”</td>
<td>5°43’297”</td>
<td>59</td>
<td>团状碳酸盐与粒状碳酸盐</td>
<td>Pliocene?</td>
</tr>
</tbody>
</table>

Fig. 2. – Geological map of onshore southern Provence, modified after the BRGM geological map of Marseille 1/250,000 [Rouire and Blanc, 1979] and offshore Provence continental shelf (this study). Plio-Quaternary deposits (Unit 6) are mapped when its two-way time thickness is higher than 100 ms (two-way time).
post-Jurassic seismo-stratigraphic units to be identified and mapped across the Provence continental shelf (fig. 2). The acoustic basement (Us) is characterized by an unstructured seismic facies ranging from chaotic to transparent. It correlates with the Paleozoic metamorphic basement (samples CR40, CR41, CR42, CR43: table II; samples m1, m2, m3, m4: table III), the late Paleozoic (Carboniferous and Permian: sample p1, table III) deposits and part of the Mesozoic (Triassic to Jurassic: samples d2, d2, d3, d4, table III) sedimentary cover (fig. 3 and 4).

Unit U0 (Berriasian to Barremian).

The U0 unit was distinguished from the underlying Us unit only on sparker profiles, where it exhibits in its lower part a set of tectonically deformed and poorly continuous reflectors (fig. 5). This stratified interval (U0a) is interpreted to represent Berriasian to Hauterivian limestone and argillaceous limestones. The sea-bottom sample v1 (table III) collected within this stratified seismic facies interval yielded a lower Valanginian age [Froget, 1974]. The upper part of the
unit exhibits generally a non-stratified seismic facies (U0b) and likely correlate with the Upper Hauterivian and Barremian massive limestones and dolomites (fig. 6 and 7). On airgun profiles, the U0 unit exhibits a chaotic facies that cannot be distinguished from the underlying Us unit. Onshore, the thickness of Berriasian to Barremian deposits may reach 750 m in the Marseille area whereas offshore the two-way time thickness of the U0 unit is higher than 0.2 s (approximately 600 m by considering a velocity of 6000 m/s in Urgonian tight limestones after Fournier et al. [2011]).

Unit U1 (Aptian-Albian)

The unit U1 was identified on both sparker and air-gun profiles as being composed of a well stratified seismic facies with low-frequency, continuous, parallel and folded reflectors (fig. 5, 7, 8, 9, 10 and 11). An upward transition in seismic facies, from chaotic to layered, is commonly observed between U0 and U1 units (fig. 7). An Aptian to Albian age was assigned to this seismic unit based on the following three criteria: 1) samples dredged from this unit...
(samples a1, a2, a3, a4, a5 and a6: table III) are black marls and glauconitic, siliceous sponge-rich limestones that exhibit similar facies to that of Aptian and Albian outcrops from the Toulon area [Froget, 1971]. 2) the stratified seismic pattern suggests sharp and high-frequency vertical variations in lithology that are consistent with limestone-marl alternations, and 3) unit U1 is in apparent stratigraphic conformity with the top of unit U0 (Urgonian limestones). The vertical change in seismic facies from chaotic to layered may represent an upward transition from the massive Urgonian limestones to well-stratified Bedoulian limestones and argillaceous limestones. The base of the unit U1 therefore represents the drowning-event of the Urgonian platform. Onshore, in Cassis area, the thickness of the Bedoulian-Gargasian interval is around 150 m. Offshore, south of the Riou island, the estimated thickness of U1 unit is 1100 to 1600 m (fig. 11) by taking an interval velocities ranging, respectively, from 3500 to 5000 m/s. In the bay of Marseille, south of the Nerthe massif, the two-way time thickness of the U1 unit may reach 0.8 s (fig. 9) which corresponds to a thickness ranging from 1400 m to 2000 m (with interval velocities ranging respectively from 3500 to 5000 m/s).

Unit U2 (Upper Cretaceous)

The unit U2 unconformably overlies unit U1 (Aptian-Albian). Unit 2 was recognized between Cassis and Saint-Cyr-sur-Mer, South of Soubeyran cliffs (fig. 7), in the bay of La Ciotat (fig. 3), south of the Riou island (fig. 11), and in the bay of Marseille, south of the Nerthe massif (fig. 9). U2 unit reflectors exhibits onlap and/or downlap terminations over U1 unit, south of the Riou island (fig. 11) and in the bay of Marseille (fig. 9). In high-resolution sparker profiles, this unit display in its lower part a well stratified seismic facies, with high-frequency, low to medium amplitude reflectors (fig. 7). South of La Ciotat, the top of this unit is characterized, on air-gun profiles, by deformed, low continuity reflectors (fig. 3). By comparison with the formations identified onshore, unit U2 is assigned to the Upper Cretaceous (Cenomanian to Santonian) on the basis of the following arguments: 1) a sea-bottom core sample (CR57b: table II) extracted in the bay of Cassis at the base of the unit yielded the Hedbergella – Rotalipora foraminiferal assemblage that indicates a Cenomanian age [Tassy, 2012], 2) the unconformable contact between U1 and U2 is comparable to the angular unconformity between Aptian (Gargasian) marls and Cenomanian quartzose limestones observed onshore in Cassis (fig. 7) , and 3) the well-stratified seismic pattern in the lower part of unit 2 is consistent with alternating argillaceous limestone-marl alternations (Cenomanian to Lower Turonian). The seismic facies change, from stratified to chaotic, at top of Unit 2 is in agreement with the transition from basinal limestone-marl alternations of the Cenomanian-Lower Turonian [Jolet, 1996] to complex sedimentary architectures of the mid-Turonian to Coniacian
FIG. 6. – VHR sparker seismic image and interpretation of profile MSL08-120c, located west of Planier Island (see location in fig. 1 and 21). U0b: Lower Cretaceous (Hauterivian-Barremian); U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

FIG. 7. – VHR sparker seismic image and interpretation of profile CAS09-spk08b, located in the bay of Cassis (see location in fig. 1). U0b: Lower Cretaceous (Hauterivian-Barremian); U1: Aptian-Albian; U2: Upper Cretaceous; U6: Plio-Quaternary.
interval consisting of basinal quartzose calcarenites interbedded with redeposited carbonate bodies (olistolithes, breccia and calciturbidites) and Gilbert-delta bottomset conglomerates [Floquet and Hennuy 2003].

Onshore, the total thickness of the Upper Cretaceous marine deposits of the Beausset syncline (Cassis-La Ciotat area) averages 1600 m [Fournillon, 2013]. Offshore, the maximal two-way time thickness of the assumed Upper Cretaceous deposits (unit U2) is 0.6 s (~1000 to 1500 m with interval velocities ranging respectively from 3500 to 5000 m/s), in the bay of Marseille, (fig. 9), whereas in the Riou syncline it is higher than 0.1 s (~175-250 m).

Unit U3 (Rupelian-Chattian)

The U3 unit is identified in the bay of Marseille and is characterized by a stratified seismic facies with medium-low frequency, high amplitude, folded reflectors both on sparker

![VHR seismic images and interpretation of profiles A) CALMAR-5004 and B) MSL08-58, both located north of Frioul islands, on the southern margin of the Oligo-Miocene Marseille extensional basin (see location in fig. 1 and 21). U1: Aptian-Albian; U3-4: syn-rift to early post-rift (Rupelian to early Burdigalian).](image)
and air-gun profiles (fig. 12). This unit has been identified mainly north of the bay of Marseille where it is unconformably overlain by the U4 unit. U3 unit is in most cases difficult to distinguish from the overlying U4 unit. As a consequence, units U3 and U4 have been grouped as one single unit in the geological map of the offshore continental shelf (fig. 2). Unit 3 is interpreted to represent Lower Oligocene (Rupelian) continental deposits, based on the following criteria: 1) two cored samples (CR18 and CR19: table II) from this unit are pedogenetized (palustrine?) limestones with ostracods and freshwater gastropods that are similar in depositional facies to Rupelian continental carbonates from the Marseille basin [Nury, 1988; Tassy, 2012], 2) unit 3 occurs in structural continuity with the Rupelian continental deposits from L’Estaque area, in the Marseille Oligocene basin, and 3) well stratified seismic facies is consistent with sharp and rapid vertical variations in lithology (limestone, clays and sandstones).

Unit U4 (Chattian-Lower Burdigalian)

The unit 4 (U4) is made of a set of parallel, continuous, high-frequency, folded reflectors. In the bay of Marseille, this unit is conformable or slightly unconformable on unit 3 (fig. 12 and 13). Unit 4 is not distinguished from unit 3 in the southern bay of Marseille and south of the Frioul islands. Units 3 and 4 are affected by post-depositional tectonic deformation characterized by E-W trending folds. Unit 4 has been attributed to Chattian to lower Burdigalian syn-rift to early post-rift deposits [Oudet et al., 2010] on the basis of the structural continuity with the onshore outcrops (fig. 14, 15 and 16). The top of unit 4 is correlatable onshore with the top of the “biodetrital Sausset-les-Pins unit” (SB2 unconformity sensu Oudet et al. [2010]) that was interpreted to represent the top of the early post-rift “Lower Transgressive Group” of Gorini et al. [1993]. In the upper part of unit 4, south of La Nerthe massif, between
Fig. 10. – Seismic image and interpretation of profile MARION, across the Calanques shelf (see location in fig. 1). U0: Lower Cretaceous (Berriasian to Barremian); U1: Aptian-Albian; U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

TABLE III – Seabed rock samples from dredging surveys [after Froget, 1974]

<table>
<thead>
<tr>
<th>Sample name</th>
<th>X</th>
<th>Y</th>
<th>Water depth (m)</th>
<th>Sample description</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>43°08.160</td>
<td>5°25.490</td>
<td>90</td>
<td>Wurm IV-Holocene</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>43°04.285</td>
<td>5°21.760</td>
<td>150</td>
<td>Wurm III-IV</td>
<td></td>
</tr>
<tr>
<td>R45-R84-R88-R139-R180</td>
<td>43°08.150</td>
<td>5°27.600</td>
<td>250-500</td>
<td>argillo-calcic sand</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R6</td>
<td>43°08.150</td>
<td>5°27.600</td>
<td>150-200</td>
<td>red algal calcarenite and calcite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R109-R110</td>
<td>43°06.580</td>
<td>5°32.720</td>
<td>150-201</td>
<td>red algal calcarenite and calcite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R15</td>
<td>43°01.180</td>
<td>5°30.900</td>
<td>270</td>
<td>Halimeda limestone</td>
<td>Upper Miocene</td>
</tr>
<tr>
<td>R16</td>
<td>43°01.180</td>
<td>5°30.900</td>
<td>220</td>
<td>Halimeda limestone</td>
<td>Upper Miocene</td>
</tr>
<tr>
<td>R165</td>
<td>43°06.315</td>
<td>5°15.450</td>
<td>275</td>
<td>foraminiferal-molluscal calcarenite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R171</td>
<td>43°06.840</td>
<td>5°15.450</td>
<td>200</td>
<td>foraminiferal-molluscal calcarenite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R181</td>
<td>43°06.840</td>
<td>5°15.450</td>
<td>170</td>
<td>conglomerate</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R17</td>
<td>43°03.03</td>
<td>5°24.360</td>
<td>150</td>
<td>red algal calcarenite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R18</td>
<td>43°03.03</td>
<td>5°24.360</td>
<td>190</td>
<td>red algal calcarenite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R20</td>
<td>43°04.235</td>
<td>5°30.220</td>
<td>30-340</td>
<td>red algal calcarenite and calcite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R51</td>
<td>43°03.03</td>
<td>5°24.360</td>
<td>180-200</td>
<td>red algal calcarenite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>R47</td>
<td>43°05.920</td>
<td>5°27.210</td>
<td>200</td>
<td>molluscal-algal calcarenite</td>
<td>Pliocene</td>
</tr>
<tr>
<td>a1</td>
<td>43°07.150</td>
<td>5°28.200</td>
<td>150</td>
<td>marls and glossoconic limestones</td>
<td>Aptian</td>
</tr>
<tr>
<td>a2</td>
<td>43°05.400</td>
<td>5°25.800</td>
<td>220</td>
<td>marls and glossoconic limestones</td>
<td>Aptian</td>
</tr>
<tr>
<td>a3</td>
<td>43°05.300</td>
<td>5°26.100</td>
<td>200</td>
<td>marls and glossoconic limestones</td>
<td>Aptian</td>
</tr>
<tr>
<td>a4</td>
<td>43°08.150</td>
<td>5°31.400</td>
<td>150</td>
<td>siliceous limestone with Sponge spicula</td>
<td>Aptian</td>
</tr>
<tr>
<td>a5</td>
<td>43°08.300</td>
<td>5°31.000</td>
<td>320</td>
<td>marls</td>
<td>Aptian</td>
</tr>
<tr>
<td>a6</td>
<td>43°08.000</td>
<td>5°31.000</td>
<td>200</td>
<td>marls</td>
<td>Aptian</td>
</tr>
<tr>
<td>a1</td>
<td>43°08.600</td>
<td>5°29.500</td>
<td>180</td>
<td>limestone</td>
<td>Valanginian</td>
</tr>
<tr>
<td>d1</td>
<td>43°08.74</td>
<td>5°32.78</td>
<td>5</td>
<td>dolostone</td>
<td>Upper Jurassic</td>
</tr>
<tr>
<td>d2</td>
<td>43°07.08</td>
<td>5°31.150</td>
<td>160</td>
<td>dolostone</td>
<td>Upper Jurassic</td>
</tr>
<tr>
<td>d3</td>
<td>43°05.150</td>
<td>5°31.000</td>
<td>150-300</td>
<td>dolostone</td>
<td>Upper Jurassic</td>
</tr>
<tr>
<td>d4</td>
<td>43°04.150</td>
<td>5°25.300</td>
<td>200</td>
<td>dolostone</td>
<td>Upper Jurassic</td>
</tr>
<tr>
<td>m1</td>
<td>43°04.300</td>
<td>5°35.850</td>
<td>110</td>
<td>phyllite</td>
<td>Palaeozoic</td>
</tr>
<tr>
<td>m2</td>
<td>43°02.000</td>
<td>5°42.850</td>
<td>180</td>
<td>phyllite</td>
<td>Palaeozoic</td>
</tr>
<tr>
<td>m3</td>
<td>43°01.600</td>
<td>5°48.500</td>
<td>150</td>
<td>phyllite</td>
<td>Palaeozoic</td>
</tr>
<tr>
<td>m4</td>
<td>43°03.600</td>
<td>5°35.150</td>
<td>150</td>
<td>phyllite</td>
<td>Palaeozoic</td>
</tr>
<tr>
<td>m5</td>
<td>43°04.150</td>
<td>5°39.000</td>
<td>150-350</td>
<td>conglomerate with metamorphic pebbles</td>
<td>Pliocene</td>
</tr>
<tr>
<td>p1</td>
<td>43°05.250</td>
<td>5°27.000</td>
<td>200</td>
<td>Sandstone (quartzarenite) with siliceous cements</td>
<td>Permian</td>
</tr>
</tbody>
</table>
Carry-Le-Rouet and La Couronne, seismic profiles (fig. 15) exhibit a significant unconformity (envelope of toplaps terminations) that is overlain by a set of onlapping reflectors. Such an unconformity may represent the SB1 unconformity or “break-up unconformity” of Oudet et al. [2010].

A sample of benthic foraminiferal-scleractinian packstone (CR17: table II) was collected in this unit south of the Nerthe massif, that displays similar features to Chattian-Aquitanian shallow-water limestones studied onshore [Tassy, 2012]. In the onshore Marseille basin, the thickness of Oligocene deposits is higher than 800 m [Nury, 1988]. Offshore, the maximal two-way time thickness of the unit U4 is approximately 0.6 s. The average value of 44 brine-saturated P-wave velocities calculated by using Gassmann relationship from laboratory measurements of Oligo-Miocene dry outcrop samples of various lithologies and facies [Oudet, 2008] is around 3200 m/s. If one considers this value as a correct estimate of average interval velocity of Oligo-Miocene deposits, the maximum thickness of U3 and U4 units would average 960 m in the bay of Marseille.

Unit U5 (Mid Burdigalian to Messinian)

Unit 5 (U5) is characterized by a stratified, high frequency and high amplitude seismic facies. South of La Nerthe massif, this unit unconformably overlies unit U4 (fig. 17 and 18) and consists of a set of undeformed reflectors that are gently dipping to the SW (fig. 15, 16 and 17). South of Cap Couronne, unit U5 is affected by subvertical faults and short-wavelength folds of undefined orientation along a N160-trending deformation belt (fig. 17, 19 and 20). Along this deformed belt, seismic facies within Unit U5 may become almost transparent or with discontinuous, low amplitude reflectors. South of the Marseille bay, unit U5 is affected by reverse faults, at the vicinity of the contact with the Mesozoic basement (U0 unit) from the seaward prolongation of the Marseilleveyre massif (fig. 6). In the Calanques and Blauquières area, at the margin of the continental shelf, unit U5 forms a sedimentary wedge, prograding southwards, that onlaps the Mesozoic (fig. 11) or the Paleozoic basement. This unit is bounded at top by the Messinian erosional surface. The lower part of unit U5
correlates onshore with the mid to upper Burdigalian “Plan de Sausset unit” and “La Couronne Limestone unit” (fig. 14 and 15). This unit can be attributed to post-rift (“Upper Prograding Group” sensu Gorini et al. [1993]) and pre-Messinian formations [Oudet et al., 2010]. Halimeda-rich limestones (samples R15-R16: table III) were collected from this unit [Froget, 1974] south of the Blauquières bank. The maximum two-way time thickness of unit U5 is 0.2 s which would represent a thickness of approximately 320 m by considering a 3200 m/s interval velocity.

Unit U6 (Plio-Quaternary)

Unit U6 is composed of a set of parallel, subhorizontal to oblique, sometimes sigmoidal, continuous reflectors, on both sparker and air-gun profiles (e.g. fig. 4 and 17). On the Blauquières bank, this unit exhibits in its lower part a well-stratified seismic facies, with low-frequency and high amplitude reflectors. In this area, unit U6 represents the sedimentary infill of Messinian canyons [Tassy, 2012; Tassy et al., 2014]. All samples collected from this unit provided Pliocene to Pleistocene ages [Froget, 1974; Tassy, 2012; tables II and III]. Onshore, the Bandol conglomerates, assigned to the Pliocene by Coulon [1967] could represent a lateral equivalent of the offshore unit U6.

Tectonostratigraphic framework of the Provence continental shelf

The offshore Provence continental shelf can be subdivided into three main structural domains (fig. 2). The western area, south of the Nerthe massif (Côte Bleue and bay of Marseille), represents the seaward extension of the Marseille Oligocene basin (fig. 1). The central area, located between the Planier island and the Cassidaigne canyon, is a submarine plateau composed of highly deformed Mesozoic rocks which was significantly eroded during the MSC event and by marine abrasion during Plio-Quaternary transgressions [Froget, 1974; Collina-Girard, 1999]. The eastern area (Blauquières bank), extending from the Cassidaigne canyon to the Cap Sicié, is regarded as the seaward extension of the Bandol and Cap Sicié thrust-belts [Ducrot, 1967; Froget, 1974].

The Côte Bleue and the Bay of Marseille

The portion of the continental shelf bounded to the north by the Nerthe massif and to the south by the Frioul horst (fig. 2) is interpreted as the western extension of the Tertiary Marseille basin. The NE-SW-oriented Frioul horst is made of Mesozoic units U0 (Berriasian to Barremian) and U1 (Aptian-Albian) and is structured by a set of N050 faults with normal component. In the bay of Marseille, Oligo-Miocene deposits (U3 and U4) lie on a thick interval (up to
1.5 s TWT) of Aptian-Albian (U1) and Late Cretaceous (U2) basinal deposits. North of the Frioul islands, the syn-rift and early post-rift deposits (U3 and U4 units) are thick (approximately 1000 m) and are structured as a set of en echelon N080-trending synclines (figs 9, 12, 13 and 21). This deformation is sealed by post-rift deposits of the U5 unit (fig. 21) whose base is assigned to the middle Burdigalian. The relatively isopachous deposition of the U4
TECTONOSTRATIGRAPHIC FRAMEWORK OF THE PROVENCE

FIG. 15. – A) Land to sea geological cross-section based on field observations onshore and seismic interpretation offshore. Offshore, the thickness of units U4 and U5 is estimated by using a mean interval velocity of 3200 m/s. B) Interpretation of VHR sparker seismic profile MSL08-19. U0: Lower Cretaceous (Berriasian to Barremian); U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian).

FIG. 16. – A) Land to sea geological cross-section based on field observations onshore and seismic interpretation offshore. Offshore, the thickness of units U4 and U5 is estimated by using a mean interval velocity of 3200 m/s. B) Interpretation of VHR sparker seismic profile MSL08-100. U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian).
FIG. 17. – VHR sparker seismic image and interpretation of profile MSL08-19, located in the bay of Marseille (see location in fig. 1 and 21). U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary; H10 to H13: seismic horizons.
unit sediments (fig. 12 and 13) in the center of the basin strongly suggests that the major phase of N080 fold development is younger than U4 and consequently occurred as a consequence after the early Burdigalian. The contact between U3-4 deposits and the underlying Mesozoic basement of the Frioul horst (U0 and U1 units) occurs either as passive depositional onlap (fig. 12 and 22) or as a sharp structural contact along NE-SW normal faults (fig. 8). The occurrence of drag-blocks along the NE-SW faults and associated syn-sedimentary drag-syncline and anticline development (fig. 8) indicates that the set of NE-SW faults were active during the deposition of U4 unit. East of the bay of Marseille and north of the Frioul islands, the orientation of faults affecting U3 and U4 units progressively changes eastward from NE-SW to E-W (fig. 21). Southwest of L’Estaque (NE Bay of Marseille), U3-U4 deposits are affected by N080 anticlines and synclines that are slightly oblique to dominant NE-SW faults (fig. 21). South of La Couronne, U4 and U5 units are significantly deformed along a 5 km-width, N160-oriented corridor (fig. 2, 18, 19 and 20). The unconformable contact of post-rift U5 unit over syn-rift to early post-rift unit U4 in this area suggests that part of the deformation occurred prior to the middle Burdigalian. South of the Frioul islands, the Oligo-Miocene series are very thin, slightly deformed and of reduced extent (fig. 5, 14 and 21). It unconformably overlies U0 and U1 units that are affected by E-W-trending thrusts and folds. West of Planier island, flower-structure-like faults affect the post-rift unit U5, suggesting a late reactivation of syn-rift N050 faults (fig. 6). In the bay of Marseille, deformed U3 and U4 units are sharply truncated below a sub-horizontal surface, interpreted as a polyphased wave-cut surface that formed during the Plio-Quaternary marine transgressions. As a consequence, in the bay of Marseille, there is no evidence of preserved Messinian incision within the continental shelf.
The Calanques shelf

The Calanques shelf is located south of Planier island and the Calanques coastline, east of the Marseillais canyon and west of the Cassidaigne canyon (fig. 2). South of the Calanques coastline, the Cretaceous sedimentary cover (units U0, U1 and U2) is highly deformed and affected by subvertical faults with orientations ranging from N100 to N120, sealed by Neogene post-rift deposits (unit U5). South of the Riou island, a thick interval (at least 1500 m) of Aptian-Albian (Unit U1) and unconformably overlying Upper Cretaceous deposits (Unit U2) is preserved along the axis of a N070-trending syncline (fig. 4). The southern margin of the continental shelf consists of a horst structure bounded by N100 normal faults and composed of Paleozoic metamorphic rocks onlapped by post-rift deposits (Unit U5).

The Blauquières bank and the Cassidaigne canyon

The Blauquières bank and the Cassidaigne canyon represent the western seaward extension of the Sicié massif that consists of a Paleozoic metamorphic basement overlain by a Carboniferous to Jurassic sedimentary cover (Sicié-Blauquières unit). The Blauquières bank is affected by a set of canyons which are assigned to the Messinian erosional event [Tassy, 2012; Tassy et al., 2014] and which deeply incise the Paleozoic and Mesozoic sedimentary cover as well as the metamorphic basement (fig. 4). The two main incisions are merging into one single N080 oriented canyon (Blauquières canyon) and are filled with Pliocene deposits (up to 600 m thick) (fig. 2 and fig. 4). The modern Cassidaigne canyon may be regarded as a relict portion of the syn-MSC Blauquières canyon that has not been entirely filled by Plio-Quaternary deposits [Tassy, 2012; Tassy et al., 2014]. South of the Blauquières bank, Neogene post-rift deposits (U5 unit) onlap the metamorphic basement, along the shelf break (fig. 2).

Seaward extension of the Beausset syncline

Cretaceous deposits of the Beausset syncline (fig. 1) are correctly imaged in sparker profiles from Cassis to Saint-Cyr-sur-Mer (fig. 2). In the Cassis bay, Aptian deposits (Unit U1) conformably overlie the Urgonian limestone (top of unit U0) and the unconformable contact between
Aptian marls and overlying Cenomanian quartzzone calcarenite is well expressed (fig. 7). Westward between the Calanques coastline and La Ciotat, the seaward extension the Beausset syncline terminates against a nearly vertical N120 fault, which is connected onshore to the N-S trending Luminy fault system (fig. 2). South of La Ciotat, the Beausset syncline ends against the Triassic and Jurassic cover of the Bandol thrust belt. In La Ciotat bay, as evidenced onshore [Philip, 1967, 1982; Philip et al., 1987] the Upper Cretaceous unit (unit U2) from Le Beausset syncline may be overthrusted to the north by the Mesozoic cover of the Bandol thrust belt (fig. 3A) or may passively onlap the Triassic basement (fig. 3B).

DISCUSSION

New insights into the mid and late Cretaceous paleogeography and structures of Provence

The seismic interpretation of offshore profiles provides new constraints on the paleogeography of Provence during mid and late Cretaceous times. In figure 23 are mapped the occurrence and associated thickness of Aptian-Albian deposits (U1 unit) on the continental shelf. A key feature of the offshore seismic stratigraphy of Cretaceous series is the remarkable development of Aptian-Albian deposits in the bay of Marseille (up to 0.8 s two-way time thickness = 1400 to 2000 m depth converted thickness: fig. 24 a and b) and south of the Riou island (up to 0.6 s two-way time thickness = 1000 to 1500 m depth converted thickness: fig. 24c). The occurrence and regional distribution of thick Aptian-Albian deposits on the Provence continental shelf may be interpreted as resulting from various tectono-stratigraphic controls. An early, syn-depositional control on the U1 unit thickness is the southward increase in subsidence rate related to the formation of the Aptian-Albian South-Provence basin [Masse and Fenerci-Masse, 2013] that may have resulted in thicker deposition offshore. During the Durancian phase, differential uplift within the Provence area led to partial or complete erosion of the Aptian-Albian deposits. Onshore Albian deposits are reported only near Toulon [Macchour, 1988] and in scattered, small-scale outcrops around Marseille especially in La Nerthe massif. The effect of Durancian differential uplift on the preservation of lower Cretaceous deposits has been evidenced onshore in the Allauch massif [Guillonnet-Benaize et al., 2010] and La Nerthe massif [Masse, 1976]. Offshore, such differential uplift is suspected between La Nerthe massif coast where...
the Aptian deposits are relatively thin (<150 m) and capped by Upper Cretaceous formations and offshore where U1 unit is extremely thick (>1400 m) (fig. 23). The boundary between thin and thick Aptian-Albian domains is a N090 to N070 normal fault that is sealed by Tertiary deposits (fig. 9 and 23). This accident may have been active during the deposition of unit U1 as suggested by the overall E-W direction that is consistent with the orientation of the Aptian-Albian basin [Masse and Fenerci-Masse, 2013] and by the increase in unit U1 thickness toward the fault (fig. 9 and 24b). On the Calanque shelf, the thickness of Aptian-Albian deposits ranges from 150 m in the bay of Cassis to 1000-1500 m (0.6 s TWI) south of Riou island within a distance of less than 8 km (fig. 24c). Such an increase in thickness may have been driven by syn-depositional movement of a set of N090 to N110 normal faults evidenced from seismic data (fig. 23). Such faults have been probably reactivated as normal faults during the Duranian high event, as normal and/or strike slip faults during the late Cretaceous South-Provence basin formation and finally as strike-slip or reverse faults during the Pyreneo-Provençal compression as suggested by the deformation (folds and thrusts) of Lower Cretaceous formations along N110 faults on the Riou island [Monteau et al., 2005].

South of the Riou island, Aptian-Albian deposits are preserved in an E-W-trending syncline of probable Pyreneo-Provençal origin (fig. 24c).

A major issue of the seismic interpretation of the newly acquired seismic data is the mapping of the offshore termination of the Pyreneo-Provençal Sicié imbricate (fig. 2 and 23). The development of the Sicié imbricate led to substantial subsequent erosion of the whole or part of the Mesozoic sedimentary cover. As a consequence, no Cretaceous deposit is preserved on top of the Sicié imbricate in contrast to the Calanques shelf area, west of the Cassidaigne canyon.

On the Provence continental shelf, Upper Cretaceous deposits (U2 unit) are only preserved in the Riou syncline (fig. 11) and in the bay of Marseille (fig. 9) where they reach a thickness of approximately 1000-1500 m (0.6 s TWI). Such a thickness is consistent with the development of a subsiding South-Provence basin [Philip, 1970; Hennuy, 2003] during the Upper Cretaceous at the present-day continental shelf location. The Upper Cretaceous South-Provence basin has been interpreted to result from E-W strike-slip fault movements under a transtensional tectonic regime [Hennuy, 2003]. The studied seismic and core database evidenced that Paleozoic formations are present 8 km south of La Ciotat coast, and belong to the offshore extension of the Sicié imbricate. Most of the detrital grains within Upper Cretaceous deposits from the South-Provence basin are considered to be sourced from an emerged land located to south, the so-called Massif méridional [Hennuy, 2003], and are of similar composition to that of the Paleozoic metamorphic and sedimentary rocks from the Sicié cape [Redondo, 1986; Guieu et al., 1987]. The depositional dips of the prograding gilbert-delta foresets outcropping along coastal cliffs near La Ciotat, the dominant grain size and the estimated paleo-water-depth at the bottomset location suggest that the top of the foreset is located between 2 and 5 km south of La Ciotat cliffs [Hennuy, 2003]. Bestani et al. [2015] estimated that prior to the Pyreneo-Provençal shortening, the Sicié imbricate location was shifted 12 kilometers southward relatively to the Mesozoic cover from Le Beausset unit. As a consequence, the restored position of the Paleozoic submarine outcrops relatively to La Ciotat Upper Cretaceous deltaic foresets (~20 km southward from the coast) is consistent with the occurrence, at short distance, of a metamorphic massif as suggested by Hennuy [2003]. The Sicié imbricate may therefore be regarded as a displaced relic of the Upper Cretaceous Massif méridional and the source for terrigenous supplies in the South-Provence basin should be located at least 20 km south of La Ciotat cliffs.

**Evidences and timing of post-rift deformation of the Provence continental shelf**

On the Provence continental shelf, Oligocene and Lower Miocene deposits (units U3 and U4) exhibit evidences of syn-sedimentary and post-sedimentary deformations. Syn-sedimentary deformations consist of dominant NE-SW (N040 to N060) vertical faults and N050 drag-synclines and anticlines (fig. 8) whereas post-depositional deformations include N080-trending en echelon folds (fig. 13) and minor folds and faults localized along a N160 corridor south of La Couronne (fig. 18). Both N080 en echelon folds within the bay of Marseille, and localized deformation along N160 faults south of La Couronne, are sealed by the post-rift U5 unit (fig. 21). The correlations between coastal outcrops and offshore seismic profiles indicate that the top U4 unconformity would correspond to the major angular unconformity evidenced by Oudet et al. [2010] and Demory et al. [2011] at the base of the Plan de Sausset unit (fig. 14) whose age is mid-Burdigalian (NN3 calcareous nanofossil zone). Magnetostratigraphic and biostratigraphic studies [Oudet et al., 2010; Demory et al., 2011] have shown that such an unconformity would correspond to a time hiatus of approximately 2 m.y. (fig. 25), including part of the early and mid Burdigalian (20-18 Ma). Units U3 and U4 are crosscut by normal faults of dominant NE-SW orientation that is consistent with the orientation of the major L’Estaque and L’Amandier fault systems (fig. 2 and 26) identified onshore in the Oligocene Marseille basin [Nury and Raynaud, 1986; Hippolyte et al., 1991]. As suggested by the occurrence of N050 syn-sedimentary folds northwest of the Frioul islands, N050 normal faults were active during the syn-rift phase. A large part of the normal faults affecting U3 and U4 units are sealed by the post-rift U5 unit (fig. 16, 18, 19). As evidenced by Hippolyte et al. [1991], the major NE-SW (N040 to N060) normal faults have formed during the early stages of extension (Rupelian) of the Oligocene Marseille basin. The occurrence of N080 en echelon folds in the bay of Marseille is consistent with a sinistral strike-slip reactivation of the N040 to N060 faults during a compressive phase of N-S direction (fig. 26). Such a post-rift, N-S compressive phase with sinistral strike-slip reactivation of N020 to N060 faults has been evidenced onshore in the Oligocene Marseille basin by microstructural analyses [Nury and Raynaud, 1986]. The age of this N-S compression phase is estimated to range from the early to mid Burdigalian (20-18 Ma) as suggested by the time gap evidenced between top U4 and base U5 unit (fig. 25).

The deformation along the N160 corridor south of La Couronne is polyphased. The angular unconformity between U4 and U5 units suggest a first phase of deformation that is coeval with the en echelon folds development and probably related to a minor dextral strike slip reactivation.
of syn-rift N160 faults in response to the N-S compression. Later deformations affect the U5 unit and consist of N160 fault (strike-slip?) reactivation and localized folding at the vicinity of the faults thus leading to a 5 km width N160-trending corridor of deformation that is sealed by post-Messinian deposits. Flower-like structures affecting the U5 unit are evidenced southwest of Planier island and are probably related to a reactivation of N050 faults during a post-rift compressive phase. Such deformations suggest one or various post-Burdigalian and pre-Messinian episodes of compression. Onshore Provence, the timing of post-rift deformation is relatively poorly constrained. In northern Provence, the onset of Alpine compressive deformation is recorded by the subsidence inversion in the Valensole area and is believed to start during the Burdigalian times [Dubois and Curnelle, 1978] and to continue until the Langhian [Villeger, 1984]. The age of the beginning of the Alpine deformation (Burdigalian to Langhian) was confirmed by field studies along the Salon-Cavaillon fault [Molliex, 2009; Molliex et al., 2011]. Besson [2005] evidenced, in the whole western Provence area, a network of deeply incised valleys related to a hectometer-scale uplift that occurred during the Burdigalian. The oldest deposits infilling these incisions are mid-Burdigalian (NN3 calcareous nannofossil zone at the base of the sequence S1 of Besson [2005]) and can therefore be correlated with the Plan de Sausset unit from the southern flank of the Nerthe massif, and offshore, with the base of the U5 unit. The regional uplift recorded onshore by the Burdigalian incised valleys (base S1 of Besson [2005]) is therefore probably coeval with the strike-slip reactivation of N040-N060 and N160 faults and the development of en echelon folds in the bay of Marseille. The available chronostratigraphic constraints (fig. 25) indicate that the Burdigalian compression evidenced by seismic data offshore occurred when the counterclockwise rotation velocity of Sardinia with respect to stable Eurasia started to

Fig. 22. – VHR sparker seismic image and interpretation of profile MSL08-14, located on the southern margin of the Oligo-Miocene Marseille extensional basin (see location in fig. 1 and 21). U1: Aptian-Albian; U4: syn-rift to early post-rift (Chattian to early Burdigalian).
decrease (i.e. around the inflexion point of the Sardinia rotation angle through times), at least 3 Ma before the end of the rotation of Sardinia (15 Ma after Gattacceca et al. [2007]). Such a timing suggests therefore that the southward propagation of the Alpine thrust front started prior to the end of the Liguro-Provençal oceanic opening. The age of the later deformations affecting the U5 unit is poorly constrained: they occurred during or after the Burdigalian and before the MSC. Such deformations may be assigned to the Tortonian compressive phase that is well expressed onshore between the Salon-Cavaillon and Mid-Durance faults [Clauzon, 1984, 1988] and that is believed to be responsible for the reactivation of older structures such as the Concors anticlines [Clauzon et al., 2011] and for the formation of La Trevaresse massif [Chardon and Bellier, 2003] (fig. 24a).

CONCLUSION

The integrative interpretation of marine seismic and sea-bottom rock samples provides new insights into the structural and paleogeographic framework of post-Jurassic series of the Provence continental shelf. Seven major post-Jurassic seismic units have been defined from marine seismic data and a geological map of the Provence shelf has been produced. The major results of the present study regarding the mid and late Cretaceous paleogeography and structural framework are:

1) the occurrence offshore of a thick (up to 2000 m) Aptian-Albian deposition controlled by E-W-trending normal faults. Such deposits are preserved within Pyreneo-Provençal synclines or within Oligo-Miocene grabens;

2) the occurrence of thick Upper Cretaceous series (up to 1500 m) confirms the existence of an E-W elongated South-Provence through during Cenomanian to Santonian times;

3) the Sicé imbricate is a major Pyreneo-Provençal structure recognized on the Provence continental shelf. Its western boundary is located west of the Cassidaigne canyon. The Paleozoic metamorphic basement and its Mesozoic sedimentary cover is regarded as the displaced relict of the Upper Cretaceous “Massif méridional” that represents the main source of terrigenous sediments in the South-Provence basin.

These results show that quantitative structural restorations of the basement and sedimentary cover are essential for further reconstructions of a detailed and accurate paleogeographic setting of pre-Pyreneo-Provençal depositional systems.

In addition the present study provided evidences of syn-rift and post-rift deformations on the Provence continental shelf:

**Fig. 23.** – Onshore and offshore occurrence and thickness of Aptian-Albian deposits with indication of presumed mid-Cretaceous faults and major Pyreneo-Provençal thrusts.

*Estimated value in the Bay of Cassis and onshore*
4) during the rifting phase, syn-sedimentary deformations consist of dominant NE-SW (N040 to N060) vertical fault development and N050 drag-syncline and anticline formation;

5) in the bay of Marseille, the syn-rift and early post-rift deposits (U3 and U4 units: Rupelian to early Burdigalian) are structured into a set of E-W-trending en echelon folds that are interpreted to result from sinistral strike-slip reactivation of the NE-SW faults during a N-S compressive phase of early-to-mid Burdigalian age (18-20 Ma);

6) the Burdigalian compressive event recorded on the Provence continental shelf is coeval with the regional uplift recorded onshore by the Burdigalian incised valleys (base S1 of Besson [2005]);

7) minor deformations affect the post-rift U5 unit (mid Burdigalian to Messinian), particularly along a N160-trending corridor localized south of La Couronne. Such deformations are interpreted as resulting from a later, post-Burdigalian and pre-Messinian compressive phase.

Acknowledgements. – This work was funded by Action Marges and KarstEAU project. Authors thank the captains and the crew of the R/V TETHYS II ship. We particularly thank Jacques Bégot (IUEM Brest) and Fabien Paquet (BRGM) for their technical support on seismic acquisition. We would like to thank the Master SET students (Aix-Marseille University) for their contribution to the seismic acquisition in 2007 and 2009 (LM5913 surveys). We also thank S. Berné for providing seismic lines from the CALMAR cruise and IFREMER for the MARION profile.

SGF associate editor: Philippe Yamato
FIG. 25. – Chronostratigraphic constraints of the U4 (syn-rift to early post-rift) and U5 (later post-rift). Such chronostratigraphic framework is compared with the evolution of the Liguro-Provençal basin and associated rotation of Sardinia with respect to stable Eurasia [after Gattacceca et al., 2007].

FIG. 26. – Sketch of the deformation of the Tertiary Marseille basin during the Burdigalian compression.


Bache F., Oliver J.-L., Gorini C., Rabineau M., Baztan J., Aslanian D., Ducrot J. & Rouet. – Contributions à l’étude des foraminifères de la mer Noire. – Earth Planetay Science Letters, 286, 139-157.


