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

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Keywords. – 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 seismic 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 downlaping 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.

Cadre tectonostratigraphique des formations anté-pliocènes du plateau continental de Provence (golfe du Lion oriental, SE France)

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

Résumé. – Le prolongement en mer des formations et des structures provençales était jusqu’alors 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 corrélées avec les séries affleurant à terre. Une épaisse 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 subsident 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’écaille 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 réactivation en décrochement 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 par 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-burdigalienne et anté-pliocène.

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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-Provencal 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 [Réhault *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. Stampfli 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 transtensive 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; Stampfli 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 stuctures [e.g. Lutaud, 1935; Guieu, 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 Miocene 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-oligocene times such as the Salon Cavaillon fault [Molliex *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) [Hsü *et al.*, 1973; Krijgsman *et al.*, 1999; Manzi *et al.*, 2013; Roveri *et al.*, 2014 and references therein].

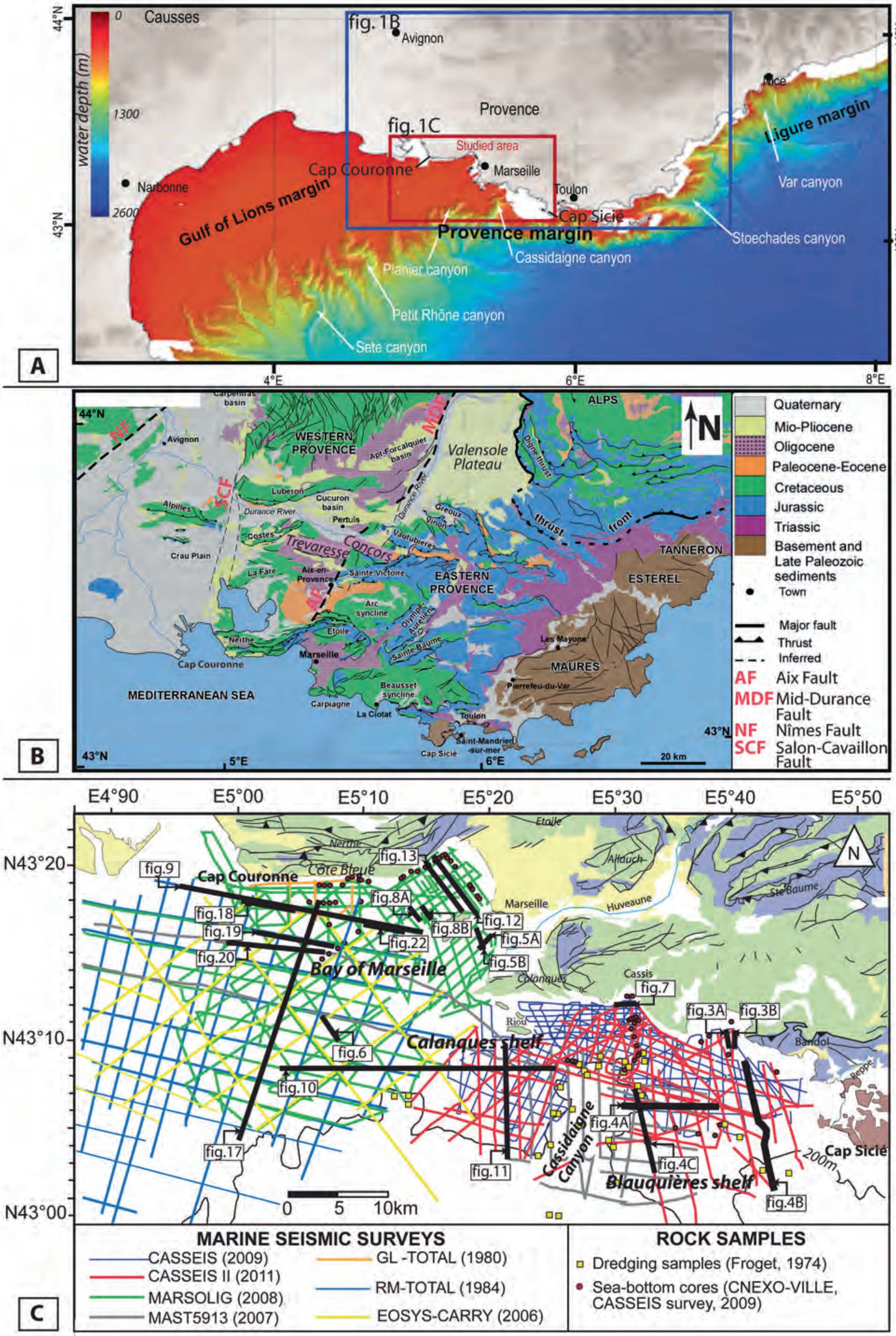


FIG. 1. – A) Bathymetric map of the Gulf of Lion, Provence and Ligurian margin (source: SHOM, IFREMER), B) Geological and structural setting of Provence, modified after Bestani *et al*. [2015], C) Location of the marine seismic profiles and cores and simplified onshore geological map.

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 on 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 anticlines 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 2D 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 km^2 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), RM84 (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 I – Summary of seismic databases used in the present paper

Seismic survey	year	Seismic source	Streamer
LM5913-2007	2007	Air gun	Multitrace (6 traces)
MARSOLIG dx.doi.org/10.17600/8450170	2008	Sparker 1000J Sparker 50J	Multitrace (6 traces) Monotrace
CASSEIS dx.doi.org/10.17600/9450130	2009	Air gun Sparker 1000J	Multitrace (12 traces) Multitrace (12 traces)
LM5913-2009	2009	Air gun	Multitrace (12 traces)
CASSEIS II dx.doi.org/10.17600/11450110	2011	Sparker 1000J	Multitrace (12 traces)

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)

CORE NAME	X	Y	Water depth (m)	CORE DESCRIPTION	AGE
CR01	43°17,972	5°20,276	39,3	Clay with red algal crusts	Quaternary
CR01b	43°17,974	5°20,302	38,9	Clay with bioclasts and rock fragments	Quaternary
CR02	43°18,112	5°20,158	40,4	Fine-grained sandstone	Quaternary
CR03	43°18,426	5°19,865	42,5	Argilaceous medium to coarse-grained sandstone	Quaternary
CR03b	43°18,432	5°19,868	45	Clay with bioclasts (Bryozoans, Mollusks)	Quaternary
CR04	43°18,563	5°19,737	49	Clay with rock fragments	Quaternary
CR05	43°18,728	5°19,593	55	Ferruginized conglomerate	Quaternary
CR06	43°19,904	5°18,474	59,2	Peloidal packstone with fresh-water gastropod molds (lacustrine limestone)	Oligocene
CR06b	43°19,885	5°18,493	59	Lacustrine limestone with gastropods	Oligocene
CR07	43°20,244	5°18,113	55,2	Medium-to-coarse-grained sandstone with angular quartz grain, calcite sparry cement	?
CR08	43°20,412	5°17,921	52,2	Clay	Quaternary
CR09	43°20,652	5°17,695	42,7	Argilaceous sand with shell fragments	Quaternary
CR10	43°20,539	5°17,417	51,2	Argilaceous sand with pebbles	Quaternary
CR11	43°20,438	5°17,167	44,2	Argilaceous sand with shell fragments	Quaternary
CR12	43°20,272	5°16,827	47,5	Argilaceous sand	Quaternary
CR13	43°20,095	5°16,411	52,5	Clay	?
CR14	43°19,962	5°16,138	50,5	Bioclastic sand, coralline crust, serpules	Quaternary
CR14b	43°19,958	5°16,135	51	Marls and bioclastic sand, coralline crust, serpules	Quaternary
CR15	43°19,926	5°16,061	51,5	Sandy Clay	Quaternary
CR16	43°19,594	5°15,343	62	Clay	Quaternary
CR17	43°19,147	5°14,293	68	Packstone with Foraminifers (miliolids), Scleractinian, Mollusks and Echinoderms	Oligo-Miocene
CR18	43°19,555	5°14,654	54,5	Carbonate mudstone with ostracods, gastropods, coated grains, circumgranular cracks (palustrine limestone)	Oligocene
CR19	43°19,33	5°14,315	60,7	Carbonate breccia with micritic elements (pedogenic breccia?)	Oligocene
CR21	43°19,383	5°10,535	20,5	Conglomerate with rounded pebbles and sparry cements	Oligocene ?
CR22	43°19,111	5°10,989	40,7	Clay with rock fragments	Quaternary
CR22b	43°19,109	5°11,989	40,2	Clay with shell fragments	Quaternary
CR23	43°19,091	5°10,676	38	Clay with shell fragments	Quaternary
CR24	43°19,079	5°9,938	25	Clay with red algae, bryozoans, mollusks, serpules	Quaternary
CR24b	43°19,078	5°9,951	31,7	red algal and oyster limestone	Oligo-Miocene ?
CR25	43°19,081	5°9,819	24,2	Recrystallized (calcitized) coral	Oligo-Miocene ?
CR26	43°18,692	5°9,492	29	Argilaceous bioclastic sand	Quaternary
CR26b	43°18,701	5°9,489	26,5	red algae and shell fragments	Quaternary
CR27	43°18,684	5°8,363	27	red algae and shell fragments	Quaternary
CR27b	43°18,701	5°7,956	33,5	red algae	Quaternary
CR28	43°18,704	5°7,477	40,7	Clay with shell fragments	Quaternary
CR29	43°17,98	5°8,386	54,2	Fine-to-medium-grained sandstone with angular quartz grain, calcite sparry cement	?
CR29b	43°17,975	5°8,392	54,7	Medium-grained sandstone, limestone pebbles with perforations	?
CR30	43°17,968	5°8,848	57,5	Clay with mollusks and red algal fragments	Quaternary
CR30b	43°17,971	5°8,815	53,7	Clay with Spondyle fragments	Quaternary
CR31	43°17,982	5°7,818	53	Medium-grained sandstone with angular quartz grain, calcite sparry cement, miliolids	?
CR32	43°17,996	5°6,658	62,7	algual mud	Quaternary
CR33	43°16,716	5°8,488	68,2	Medium-grained sandstone with angular quartz grain, calcite sparry cement, miliolids	?
CR34	43°17,888	5°11,029	54,5	algal sand	Quaternary
CR35	43°15,978	5°10,263	71,7	Quartzose calcarenite	?
CR36	43°15,552	5°9,496	73,5	Quartzose calcarenite with benthic forams	Oligo-Miocene
CR37	43°15,187	5°8,835	83,5	Quartzose calcarenite with benthic forams, echinoderms (echinoids, holothurians), leached/recrystalized mollusks.	Oligo-Miocene
CR38	43°14,883	5°8,265	88,2	Fine-grained glauconitic sandstone with sparry cements;	?
CR39	43°14,67	5°7,873	88,2	Fine-grained glauconitic sandstone with sparry cements.	?
CR39b	43°14,668	5°7,869	88	Laminated silty clay with forams and strongly compacted sandstone with calcitic sparry cement.	?
CR40	43°3,825	5°38,785	97	Phyllad	Paleozoic
CR41	43°3,325	5°38,277	93,2	Phyllad	Paleozoic
CR42	43°3,503	5°36,973	112	Phyllad	Paleozoic
CR43	43°3,883	5°35,213	127	Phyllad	Paleozoic
CR44	43°7,9391	5°27,427	320	Clay	Quaternary
CR45	43°7,976	5°27,343	290	Clay	Quaternary
CR46	43°7,986	5°27,216	246	Clay	Quaternary
CR47	43°8,034	5°26,987	148	Clay	Quaternary
CR48	43°7,243	5°31	281	Bioclastic sand	Quaternary
CR49b	43°7,343	5°31,352	123,2	Sparitic limestone	?
CR50	43°8,067	5°32,433	40	Red algal sand	Quaternary

TABLE II – follow

CORE NAME	X	Y	Water depth	CORE DESCRIPTION	AGE
CR51	43°7,821	5°32,104	83,2	Carbonate sand with red algae, mollusks, bryozoan and solitary corals	Quaternary
CR52	43°8,194	5°32,515	37,2	Carbonate sand with red algae, mollusks, bryozoan and solitary corals	Quaternary
CR54	43°8,834	5°32,424	70	Bioclastic sand	Quaternary
CR55	43°8,83	5°32,372	75	Bioclastic sand	Quaternary
CR57	43°11,823	5°31,752	48	Bioclastic sand	Quaternary
CR57b	43°11,785	5°31,762	51	Echinoderm, Red algal and foraminiferal (*Hedbergella*, *Rotalipora*) glauconitic packstone.	Cenomanian
CR58	43°11,82	5°32,204	48	Sandy clay	Quaternary
CR59	43°10,498	5°32,331	78	Sand	Quaternary
CR59b	43°10,496	5°32,297	81	Sand	Quaternary
CR60	43°10,485	5°32,208	80	Siliceous spiculite.	Aptian-Albian
CR61	43°10,364	5°31,889	81	Bioclastic sand	Quaternary
CR62	43°10,377	5°31,897	80	Qz calcarenite with sponge spicules.	Cretaceous?
CR63	43°10,351	5°31,837	82	Bioclastic sand	Quaternary
CR64	43°10,321	5°31,664	85	Quartzite	?
CR65	43°10,125	5°32,207	79	Foraminiferal peloidal Packstone Grainstone with orbitolinids and miliolids	Lower Cretaceous
CR65b	43°10,142	5°32,177	79	Microbial bindstone	?
CR67	43°10,214	5°32,403	69,6	Bioclastic sandy clay	Quaternary
CR68	43°9,846	5°32,066	85	Bioclastic sand	Quaternary
CR70	43°9,004	5°37,32	67	Qz calcarenite with sponge spicula, forams.	?
CR71	43°9,256	5°38,233	68	Fine-grained Qz sand	Quaternary
CR72	43°10	5°39,906	43,2	Fine-grained Qz sand with shell fragments	Quaternary
CR73	43°8,109	5°39,428	88	Fine-grained Qz Sand	Quaternary
CR74	43°6,829	5°43,297	59	Conglomerate with tighlty cemented glauconitic sandstone matrix and rounded limestone pebbles	Pliocene?
CR74b	43°6,829	5°43,297	59	Conglomerate with tighlty cemented glauconitic sandstone matrix and rounded limestone pebbles	Pliocene?

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.

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

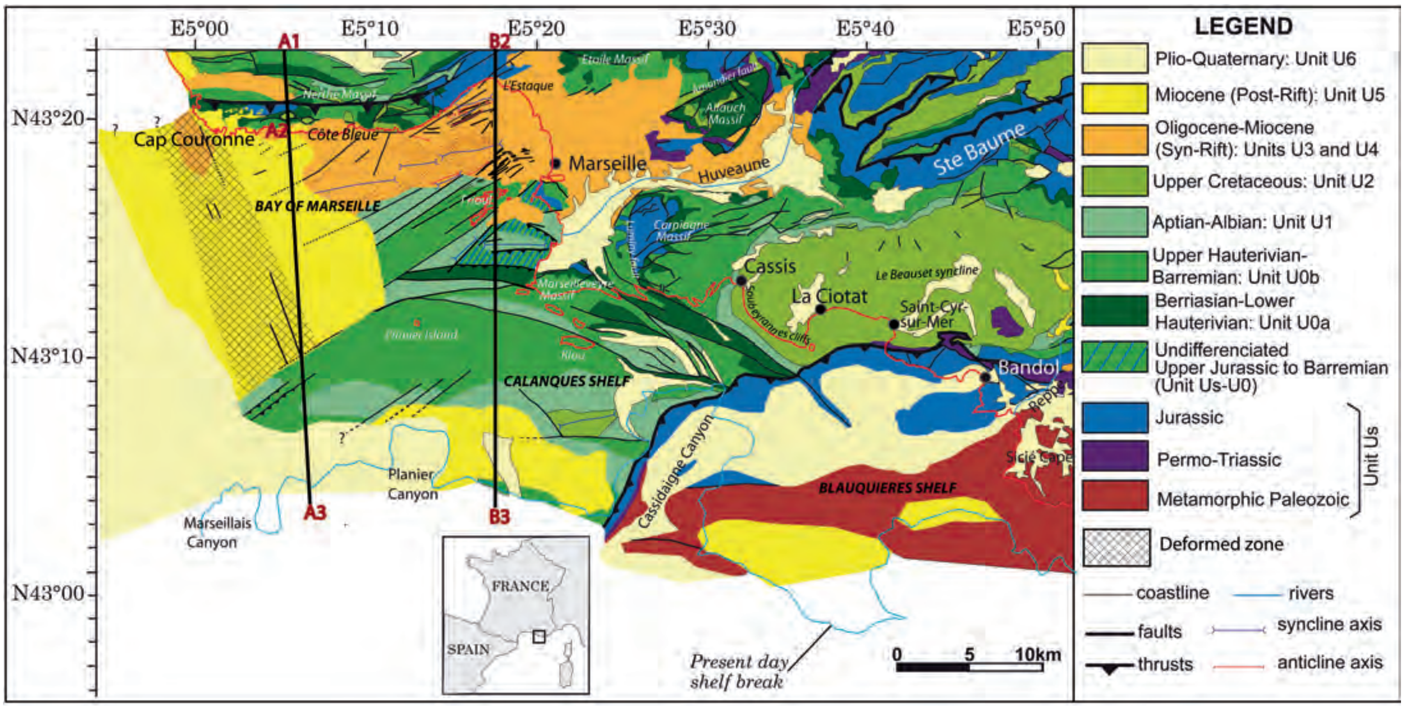


FIG. 2. – Geological map of onshore southern Provence, modified after the BRGM geological map of Marseille 1/250,000 [Rouire and Blanc, 1979] and offshore Provence continental shelf (this study). Plio-Quaternary deposits (Unit 6) are mapped when its two-way time thickness is higher than 100 ms (two-way 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 yelded a lower Valanginian age [Froget, 1974]. The upper part of the

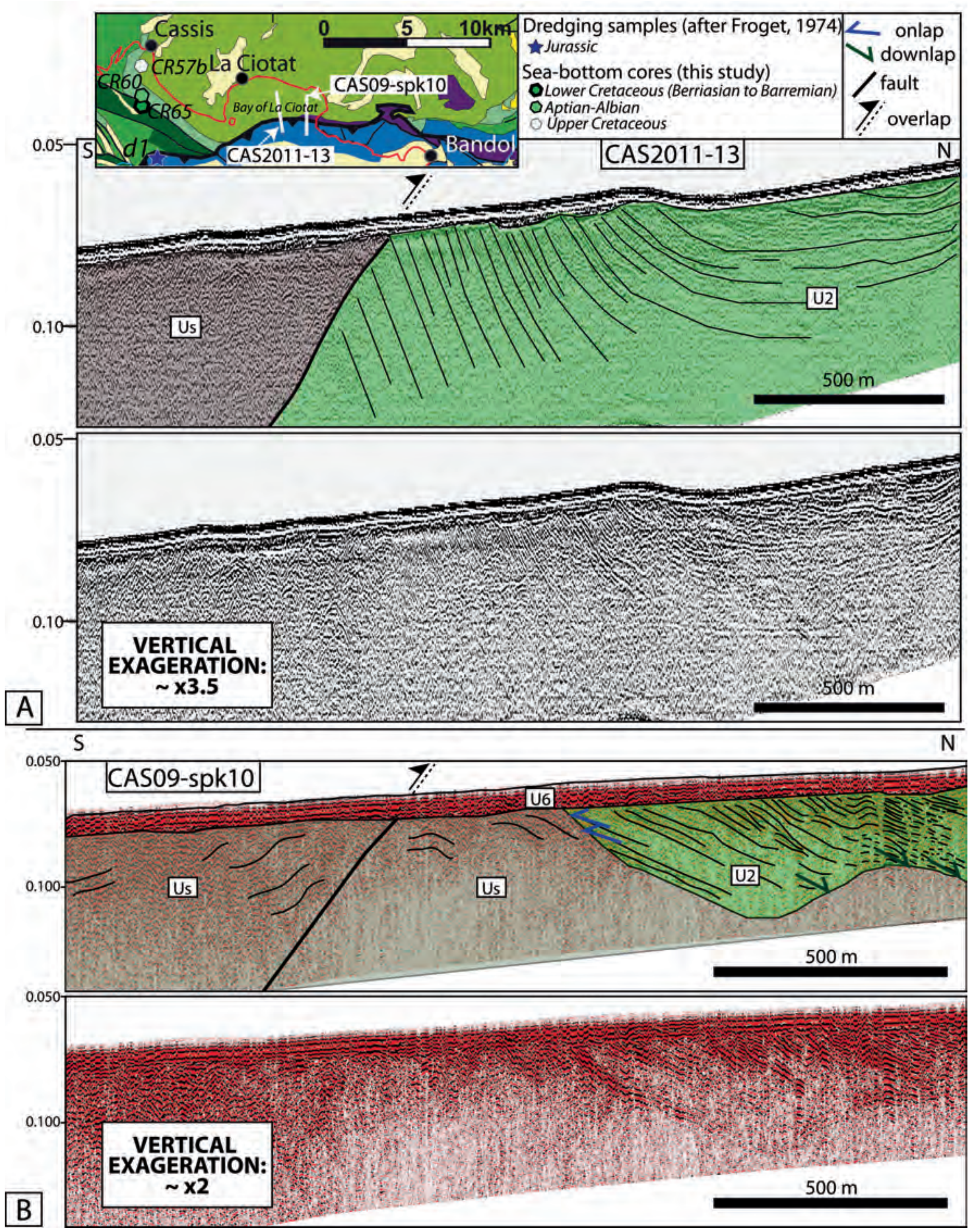


FIG. 3. – VHR sparker seismic images and interpretation of profiles A) CAS2011-13 and B) CAS09-spk10, both located in the bay of La Ciotat (see location in fig. 1). Us: acoustic basement (pre-Cretaceous); U2: Upper Cretaceous; U6: Plio-Quaternary.

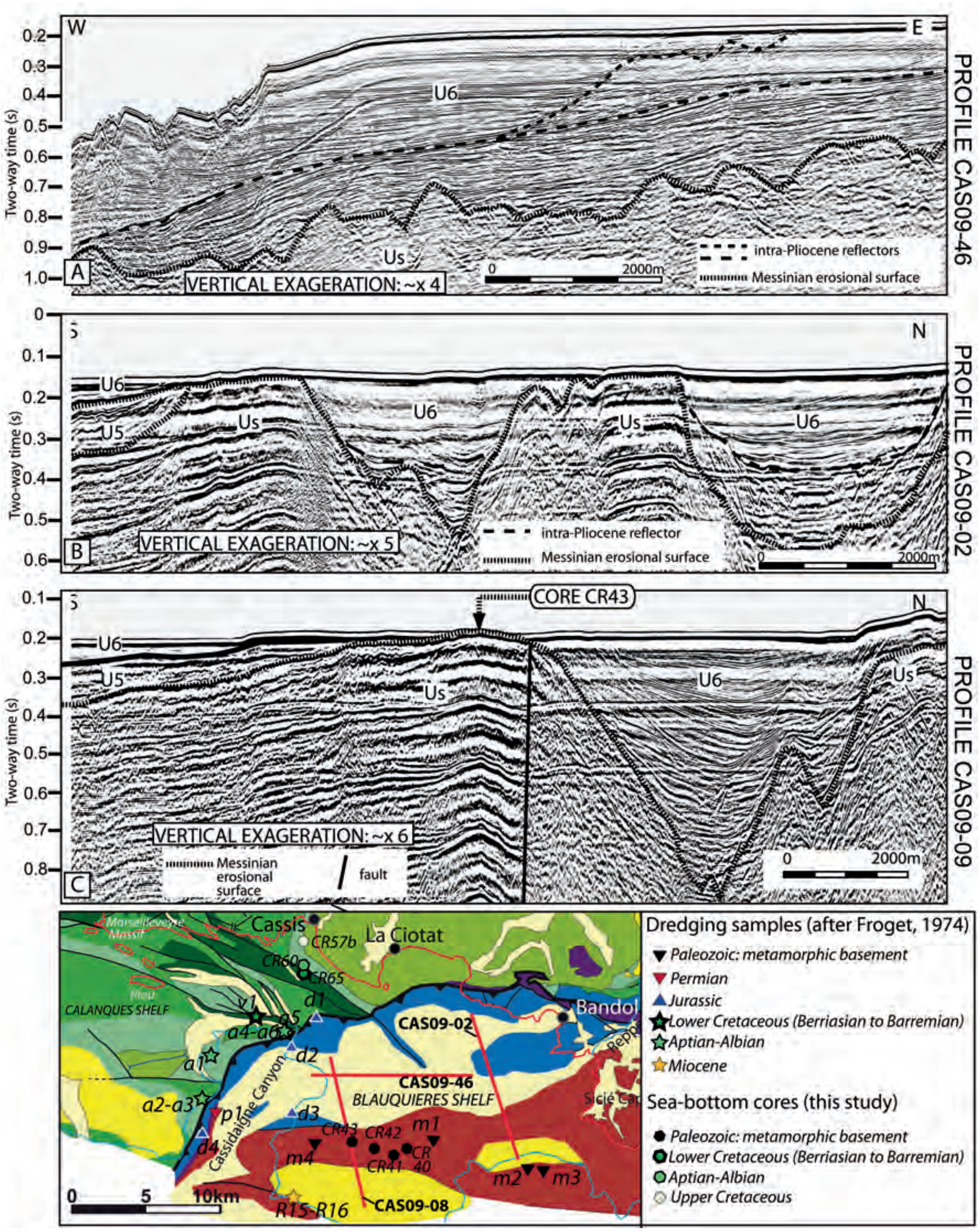


FIG. 4. – HR airgun seismic images and interpretation of profiles A) CAS09-46 and B) CAS09-02, both located in the Blauquières shelf (see location in fig. 1). Us: acoustic basement (pre-Cretaceous); U6: Plio-Quaternary.

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

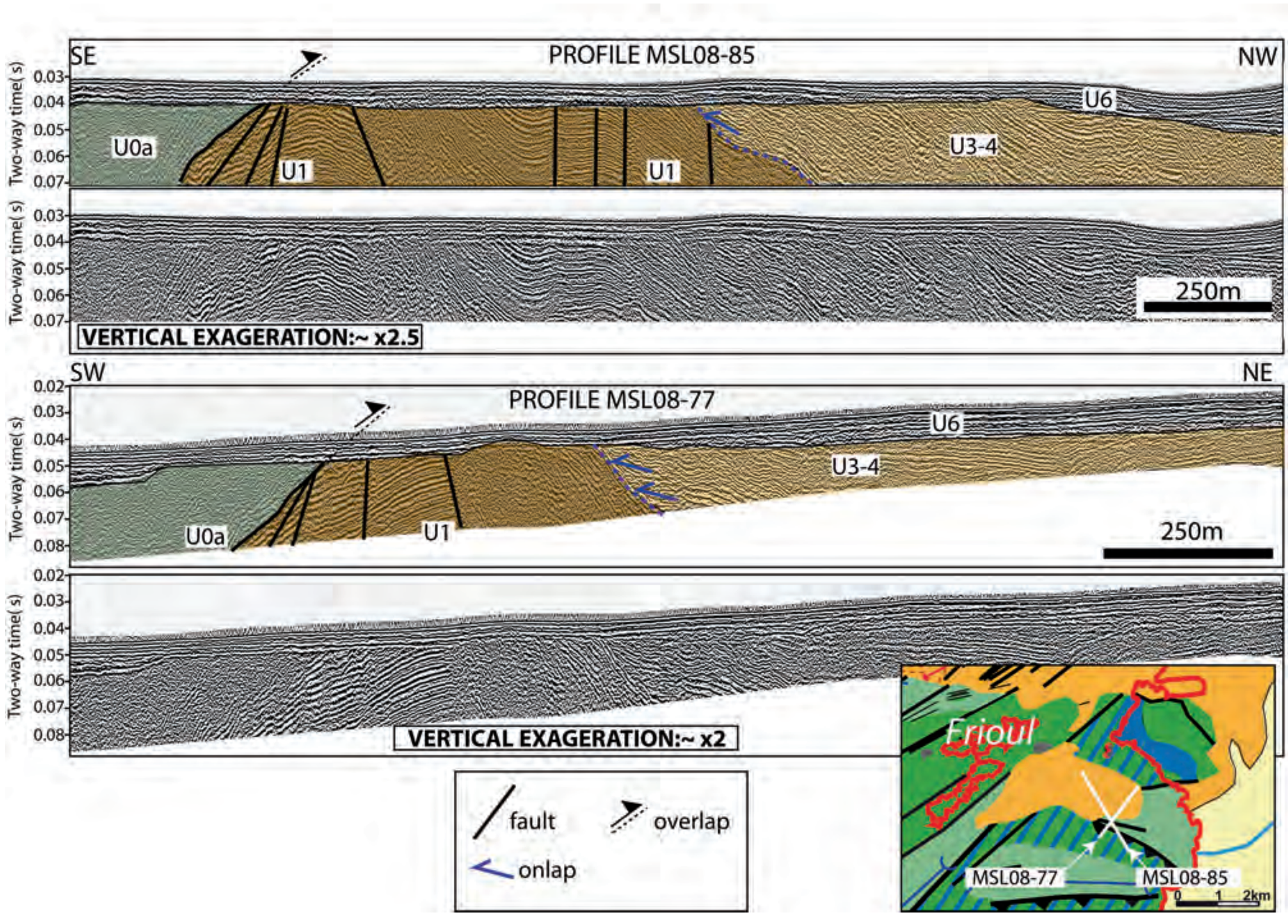


FIG. 5. – VHR sparker seismic images and interpretation of profiles A) MSL08-77 and B) MSL08-85, both located south of Frioul (see location in fig. 1 and 21). U0a: Lower Cretaceous (Berriasian to Hauterivian); U1: Aptian-Albian; U3-4: syn-rift to early post-rift (Rupelian to early Burdigalian); U6: Plio-Quaternary.

(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 Soubeyrane 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

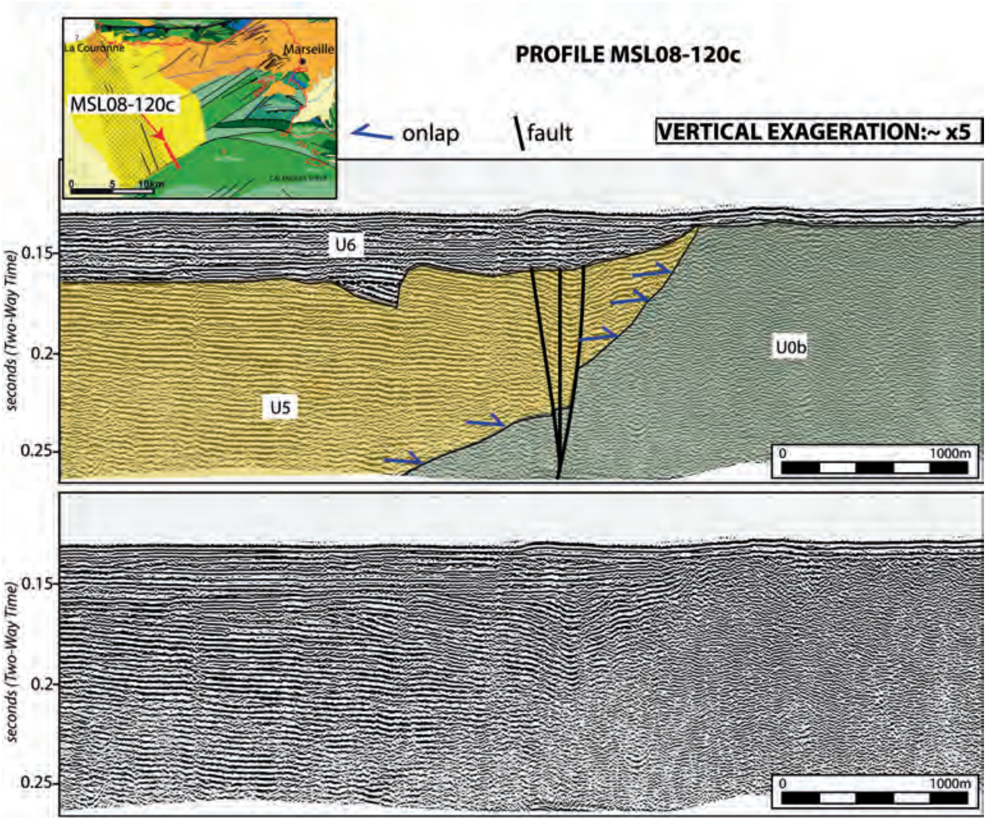


FIG. 6. – VHR sparker seismic image and interpretation of profile MSL08-120c, located west of Planier Island (see location in fig. 1 and 21). U0b: Lower Cretaceous (Hauterivian-Barremian); U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

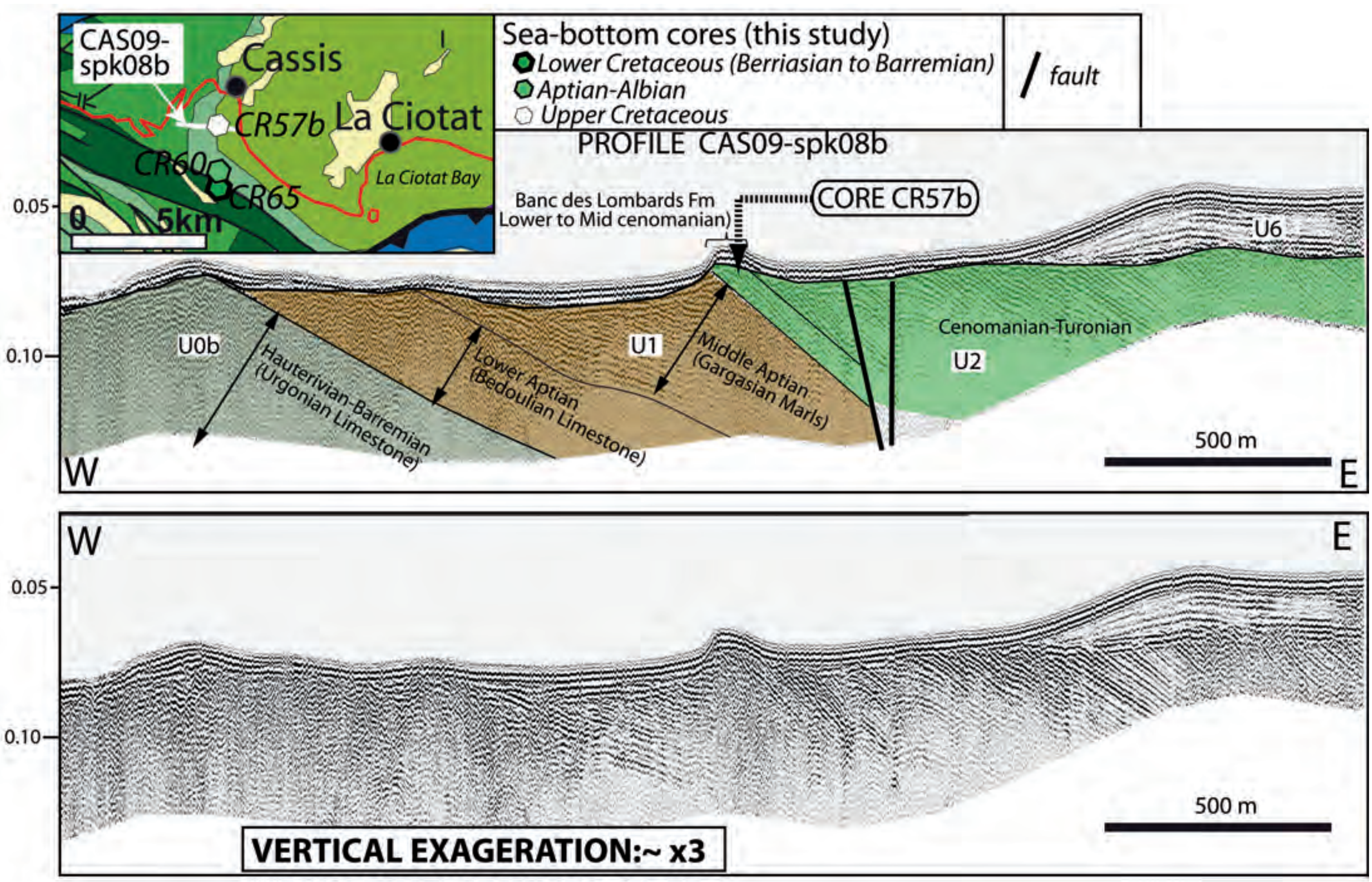


FIG. 7. – VHR sparker seismic image and interpretation of profile CAS09-spk08b, located in the bay of Cassis (see location in fig. 1). U0b: Lower Cretaceous (Hauterivian-Barremian); U1: Aptian-Albian; U2: Upper Cretaceous; U6: Plio-Quaternary.

interval consisting of basinal quartzose calcarenites interbedded with redeposited carbonate bodies (olistolites, 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

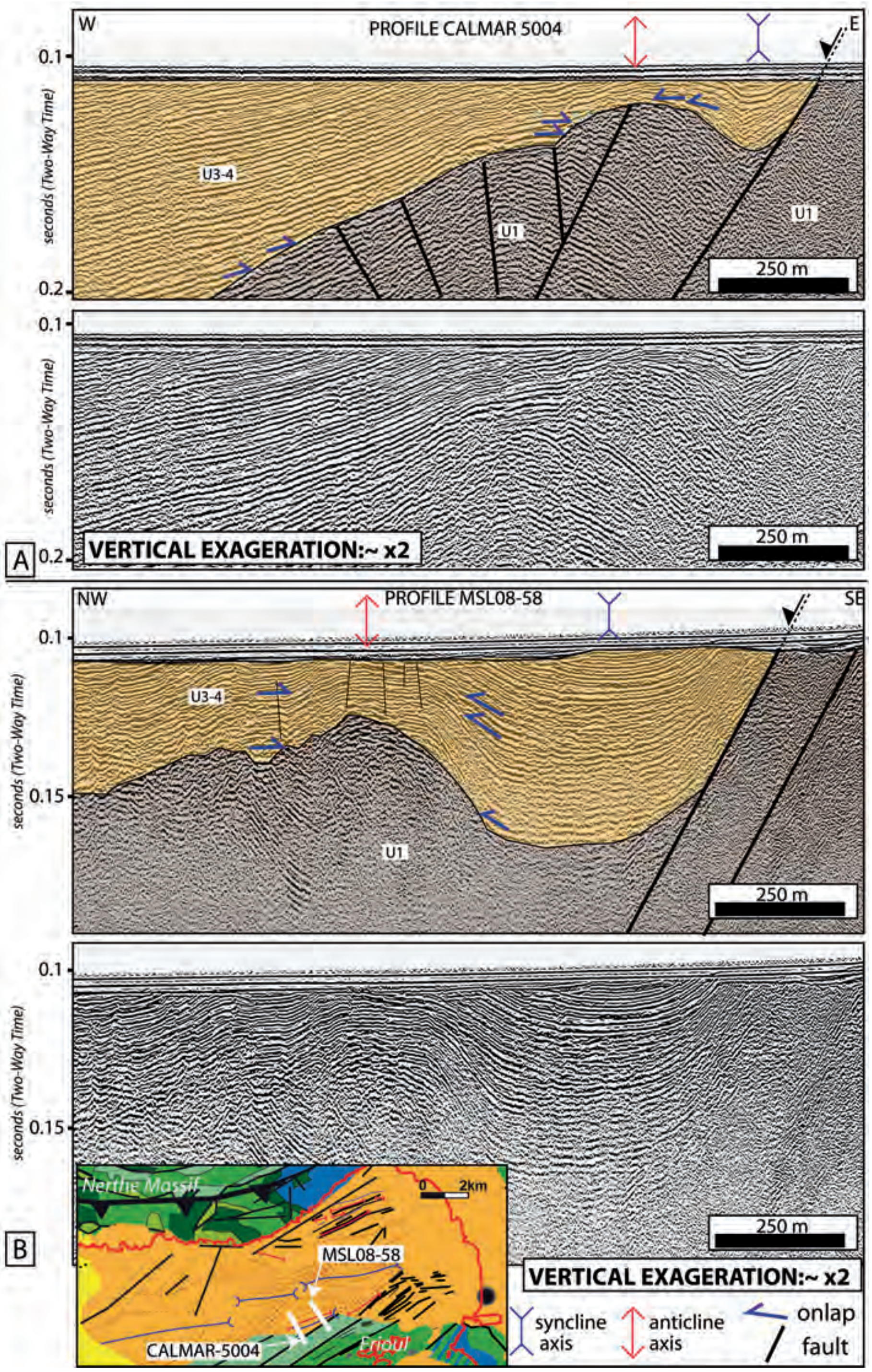


FIG. 8. – VHR seismic images and interpretation of profiles A) CALMAR-5004 and B) MSL08-58, both located north of Frioul islands, on the southern margin of the Oligo-Miocene Marseille extensional basin (see location in fig. 1 and 21). U1: Aptian-Albian; U3-4: syn-rift to early post-rift (Rupelian to early Burdigalian).

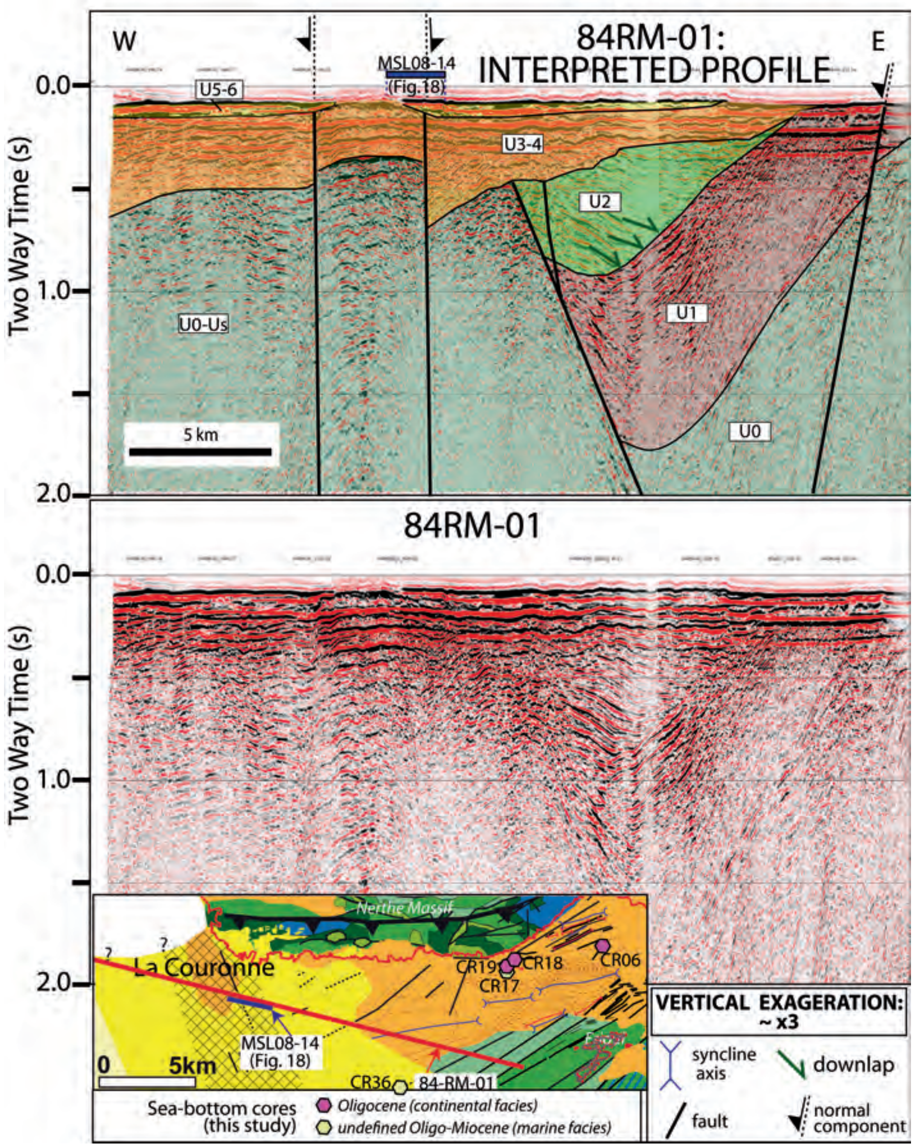


FIG. 9. – Oil-industry air-gun seismic image and interpretation of profile 84RM-01, located in the bay of Marseille (see location in fig. 1 and 21). Us: acoustic basement (pre-Cretaceous), U0: Lower Cretaceous (Berriasian to Barremian); U1: Aptian-Albian; U2: Upper Cretaceous; U3-4: syn-rift to early post-rift (Rupelian to early Burdigalian); U5-6: undifferenciated post-rift Miocene (mid-Burdigalian to Messinian) and Plio-Quaternary.

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

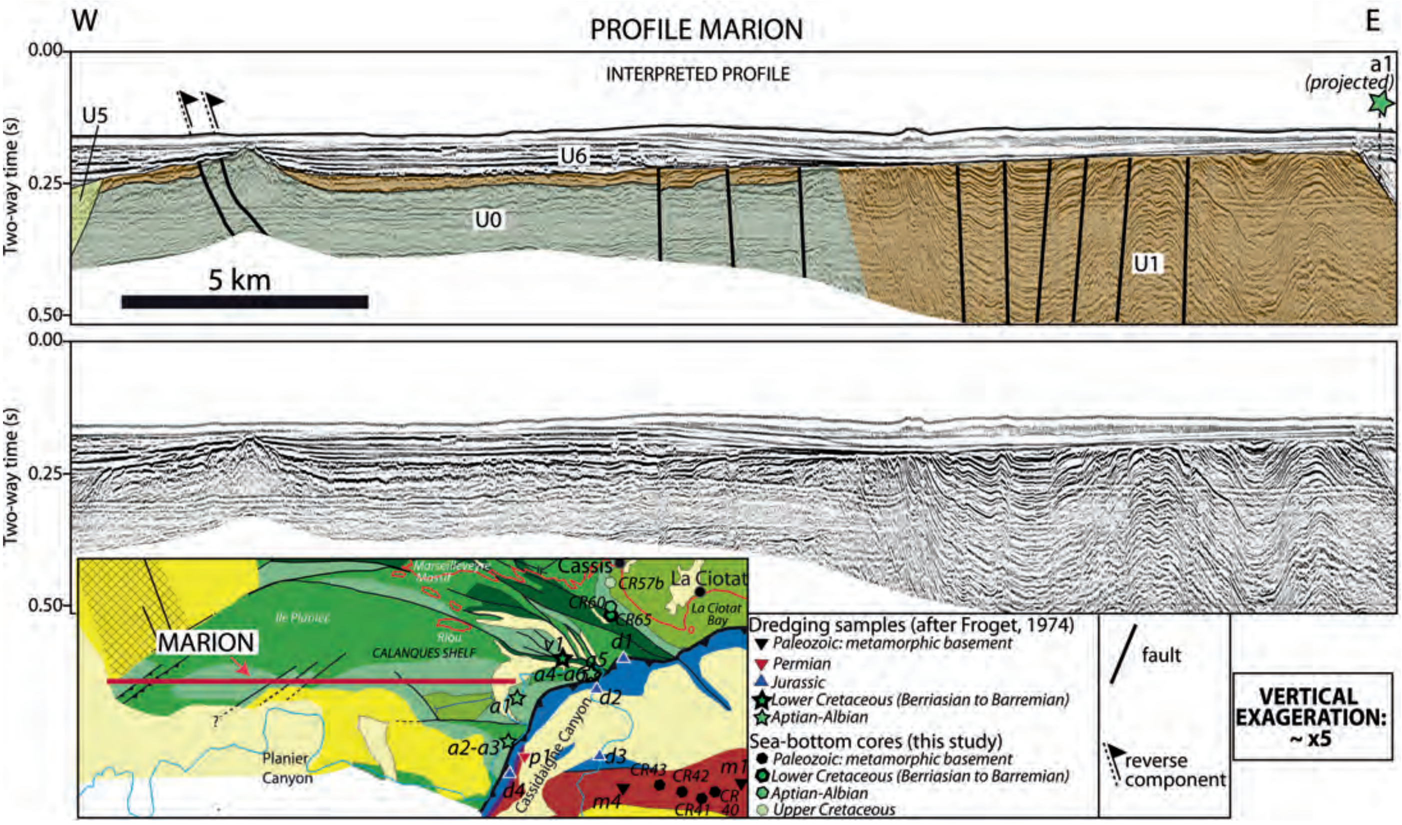


FIG. 10. – Seismic image and interpretation of profile MARION, across the Calanques shelf (see location in fig. 1). U0: Lower Cretaceous (Berriasian to Barremian); U1: Aptian-Albian; U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

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

Sample name	X	Y	Water depth (m)	Sample description	Age
C3	43°08.160	05°25.490	90		Würm IV-Holocene
C4	43°04.285	05°21.760	190		Würm III-IV
R48-R84-R88-R139-R180	43°08.150	05°27.600	250-500	argilaceous carbonate sands	Pliocene
R86	43°08.150	05°27.600	150-200	red algal calcarenite and calcirudite	Pliocene
R109-R110	43°06.580	05°32.720	150-201	red algal calcarenite and calcirudite	Pliocene
R15	43°01.180	05°30.900	270	*Halimeda* limestone	Upper Miocene?
R16	43°01.180	05°30.900	250	*Halimeda* limestone	Upper Miocene?
R165	43°06.315	05°15.450	275	foraminiferal-molluskal calcarenite	Pleistocene
R171	43°06.840	05°15.450	200	foraminiferal-molluskal calcarenite	Pleistocene
R181	43°06.840	05°13.450		conglomerate	Pleistocene
R17	43°03.03	05°24.360	170	red algal calcarenite	Pleistocene
R18	43°03.03	05°24.360	190	red algal calcarenite	Pleistocene
R20	43°04.255	05°30.220	30-340	red algal calcarenite and calcirudite	Pliocene
R51	43°03.03	05°24.360	180-200	red algal calcarenite	Pleistocene
R47	43°05.920	05°27.270	200	molluskal-algal calcarenite	Pleistocene
a1	43°07.100	05°26.200	150	marls and glauconitic limestones	Aptian
a2	43°05.400	05°25.800		marls and glauconitic limestones	Aptian
a3	43°05.300	05°26.100		marls and glauconitic limestones	Aptian
a4	43°08.150	05°31.400	150	siliceous limestone with Sponge spicula	Aptian
a5	43°08.300	05°31.000	220	marls	Aptian
a6	43°08.000	05°31.000	200	marls	Aptian
v1	43°08.600	05°29.500	180	limestone	Valanginian
d1	43°08.74	05°32.78	5	dolostone	Upper Jurassic?
d2	43°07.08	05°31.150	160	dolostone	Upper Jurassic?
d3	43°05.150	05°31.000	150-300	dolostone	Upper Jurassic?
d4	43°04.150	05°25.300	200	dolostone	Upper Jurassic?
m1	43°04.300	05°39.850	110	phyllade	Paleozoic
m2	43°02.000	05°42.850	150-200	phyllade	Paleozoic
m3	43°01.600	05°44.300	150-200	phyllade	Paleozoic
m4	43°03.600	05°33.150		phyllade	Paleozoic
m5	43°04.150	05°30.000	150-350	conglomerate with metamorphic pebbles	Pliocene
p1	43°05.250	05°27.000	200	Sandstone (quartzarenite) with siliceous cement	Permian

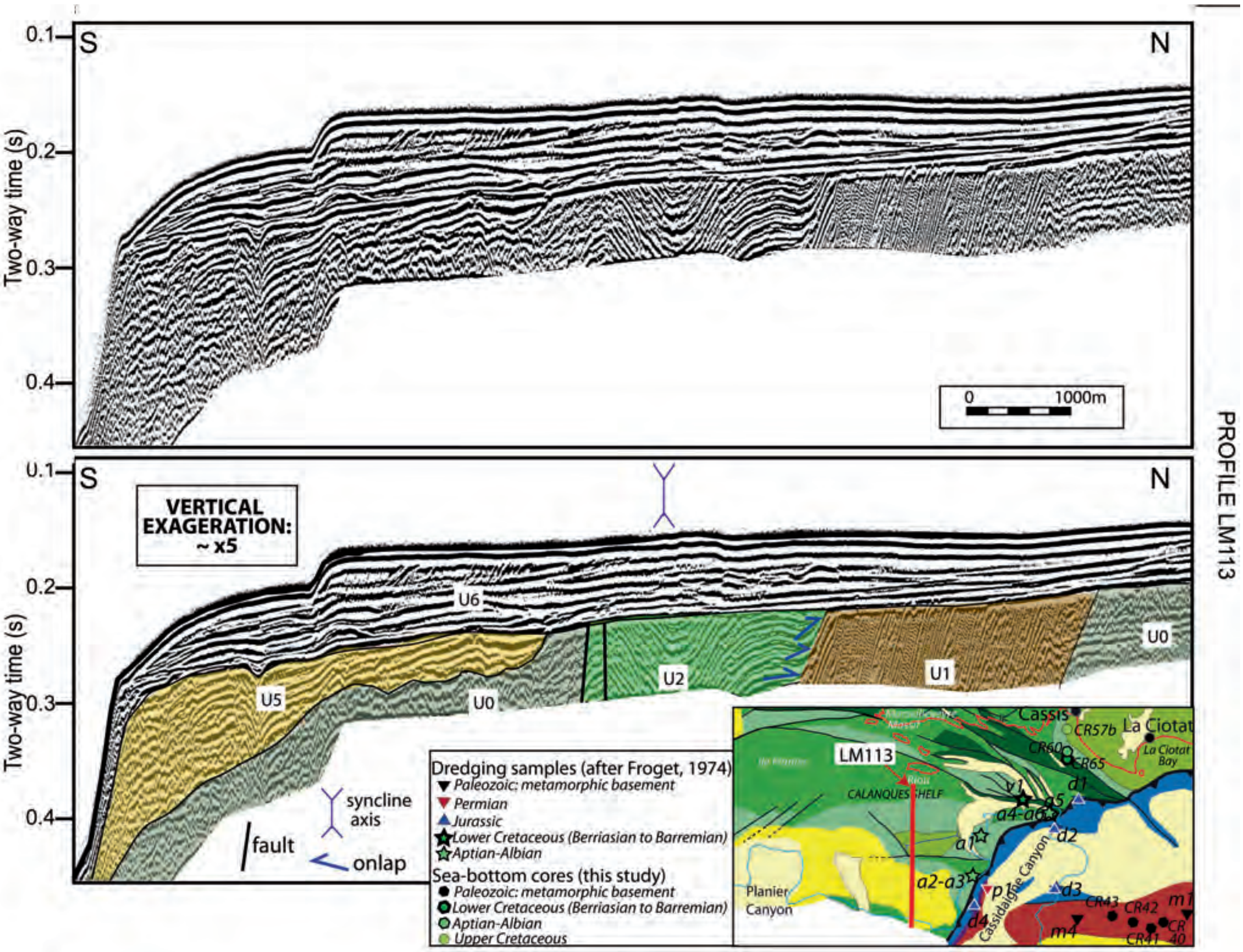


FIG. 11. – HR air-gun seismic image and interpretation of profile LM113, located in the Calanques shelf, south of Riou island (see location in fig. 1). U0: Lower Cretaceous (Berriasian to Barremian); U1: Aptian-Albian; U2: Upper Cretaceous; U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

Carry-Le-Rouet and La Couronne, seismic profiles (fig. 15) exhibit a significant unconformity (enveloppe 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

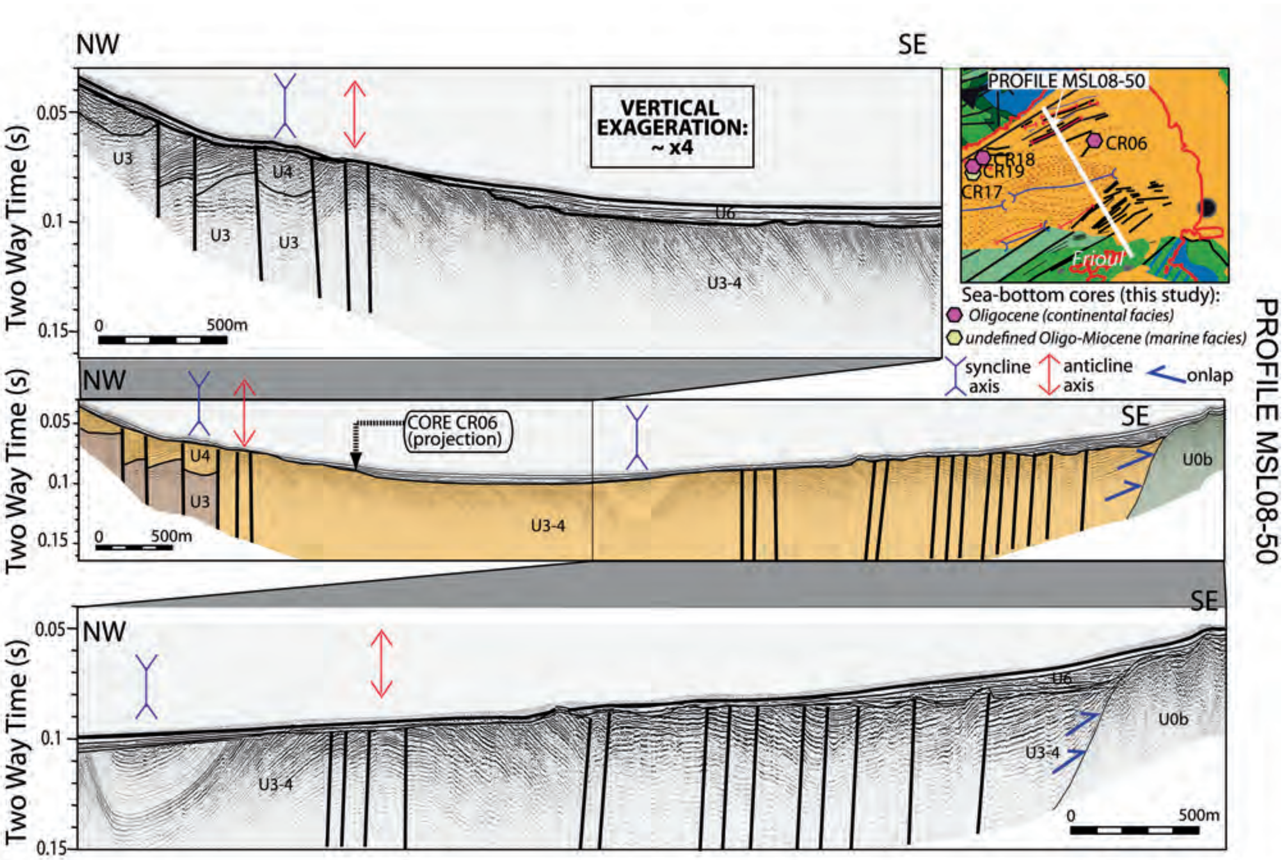


FIG. 12. – VHR sparker seismic image and interpretation of profile MSL08-50, located in the bay of Marseille (see location in fig. 1 and 21). U0b: Lower Cretaceous (Hauterivian-Barremian); U3: syn-rift (Rupelian); U4: syn-rift to early post-rift (Chattian to early Burdigalian); U6: Plio-Quaternary.

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

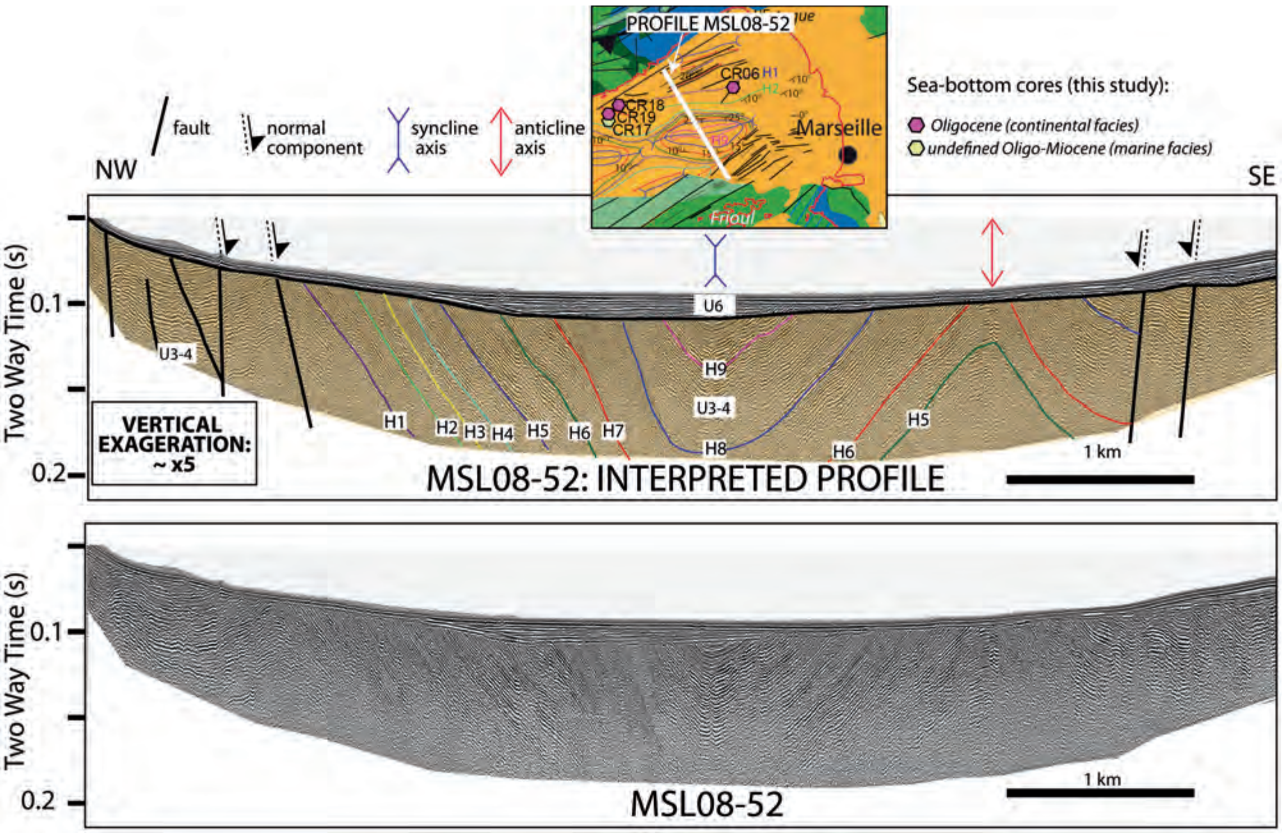


FIG. 13. – VHR sparker seismic image and interpretation of profile MSL08-52, located in the bay of Marseille (see location in fig. 1 and 21). U3-4: syn-rift to early post-rift (Rupelian to early Burdiagalian); U6: Plio-Quaternary; H1 to H9: seismic horizons.

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

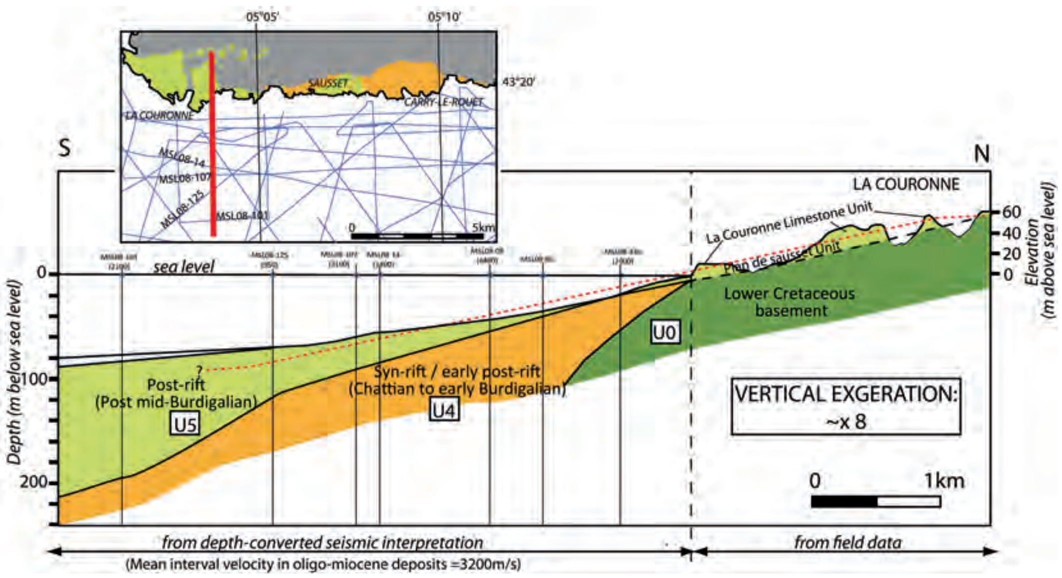


FIG. 14. – Land to sea geological cross-section based on field observations onshore and seismic interpretation offshore. Offshore, the thickness of units U4 and U5 is estimated by using a mean interval velocity of 3200 m/s. U0: Lower Cretaceous (Berriasian to Barremian); U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian). Plan de Sausset and La Couronne Limestone units have been defined by Oudet *et al.* [2010].

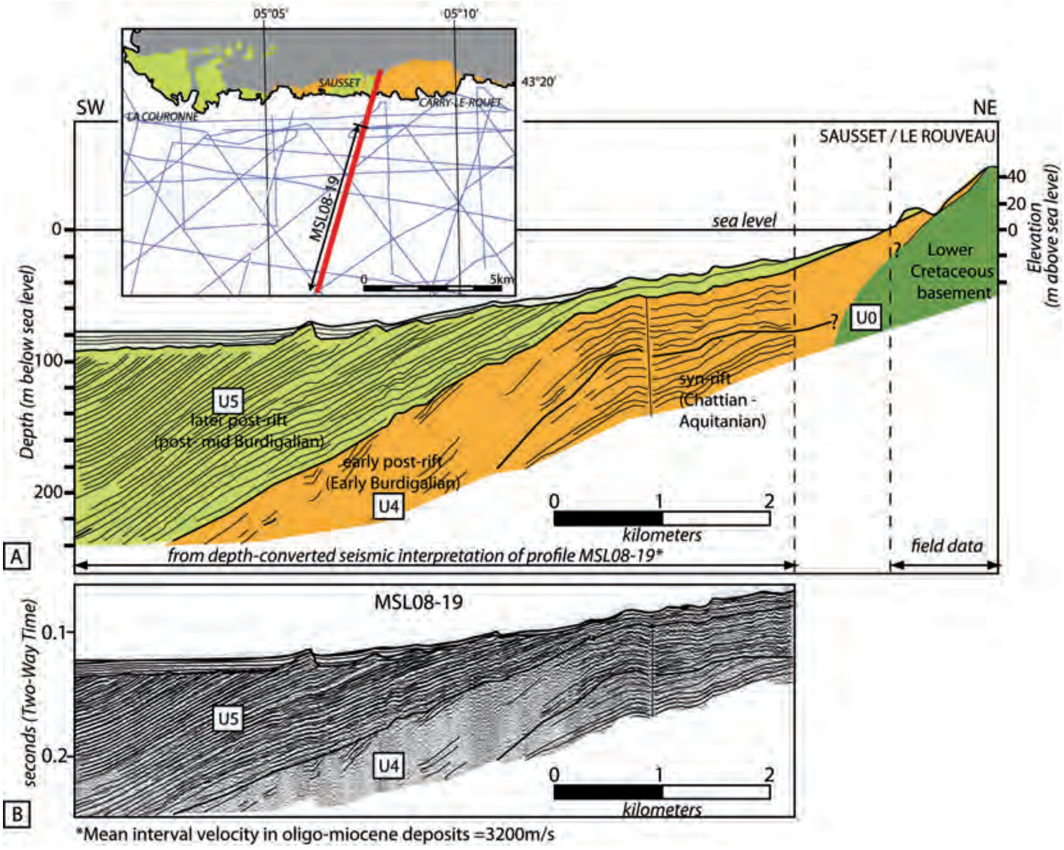


FIG. 15. – A) Land to sea geological cross-section based on field observations onshore and seismic interpretation offshore. Offshore, the thickness of units U4 and U5 is estimated by using a mean interval velocity of 3200 m/s; B) Interpretation of VHR sparker seismic profile MSL08-19. U0: Lower Cretaceous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

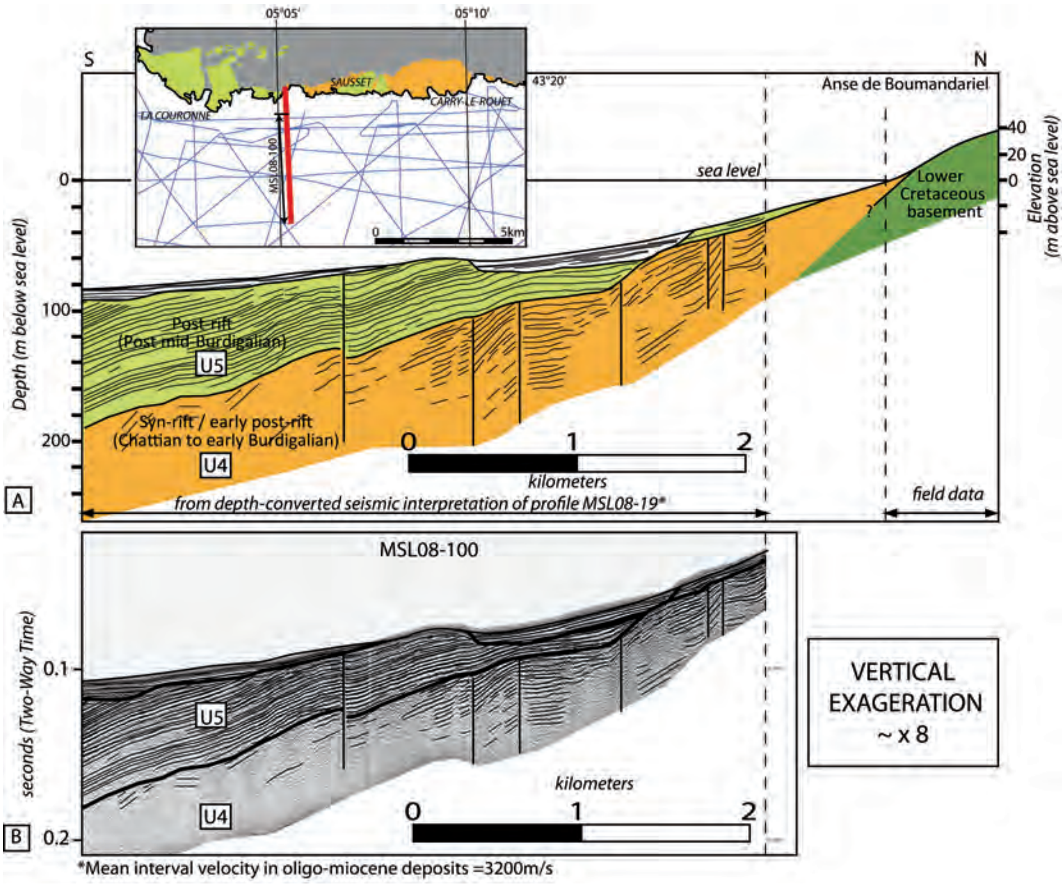


FIG. 16. – A) Land to sea geological cross-section based on field observations onshore and seismic interpretation offshore. Offshore, the thickness of units U4 and U5 is estimated by using a mean interval velocity of 3200 m/s; B) Interpretation of VHR sparker seismic profile MSL08-100. U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian).

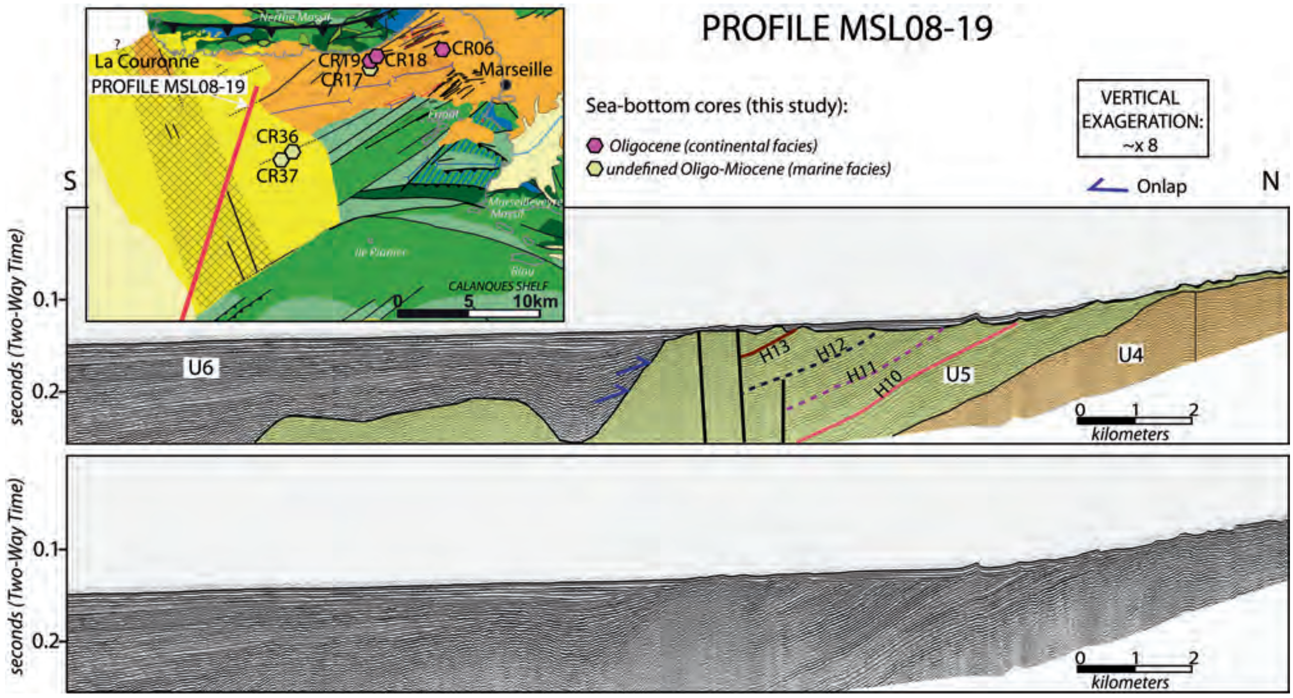
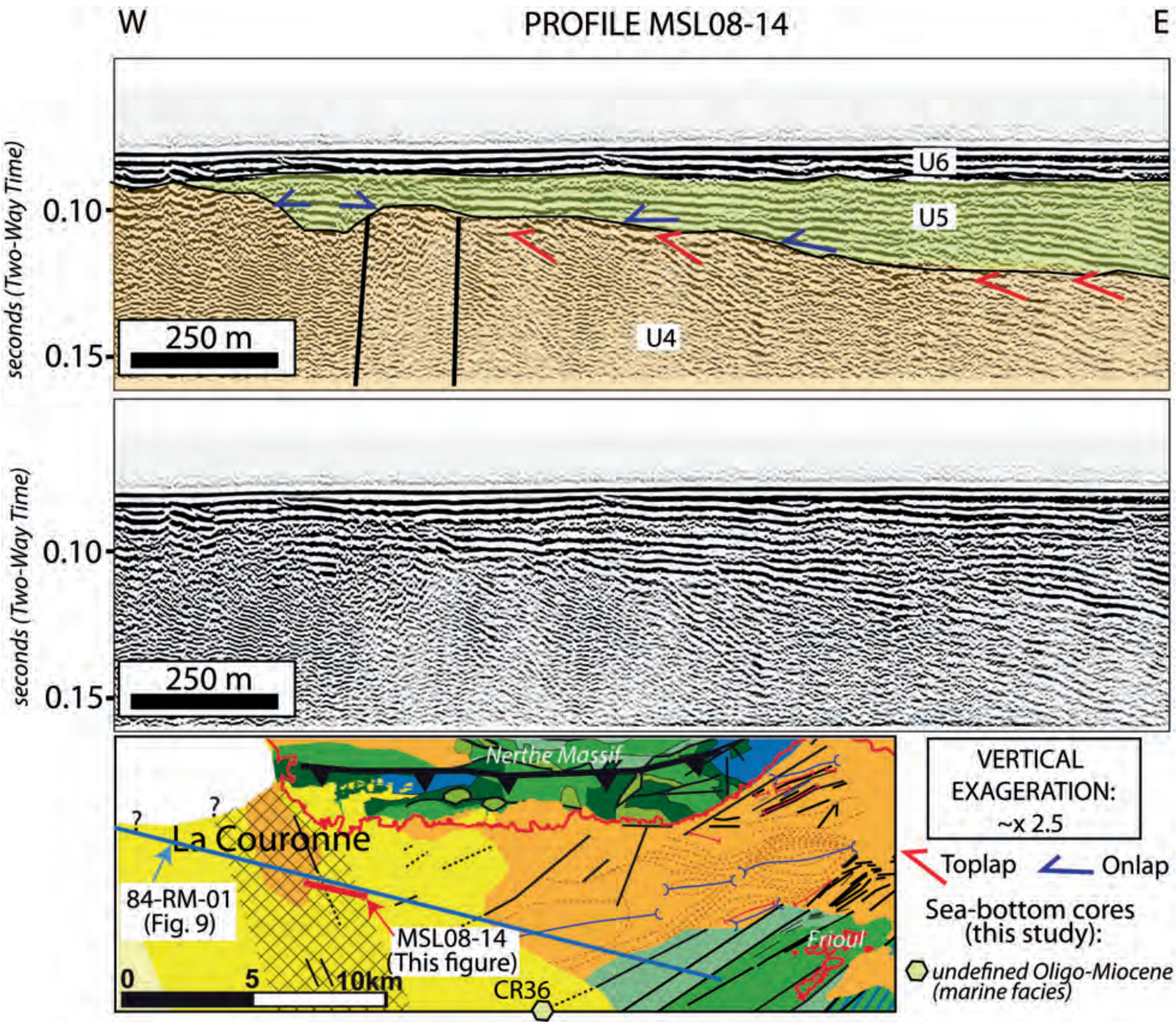


FIG. 17. – VHR sparker seismic image and interpretation of profile MSL08-19, located in the bay of Marseille (see location in fig. 1 and 21). U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary; H10 to H13: seismic horizons.



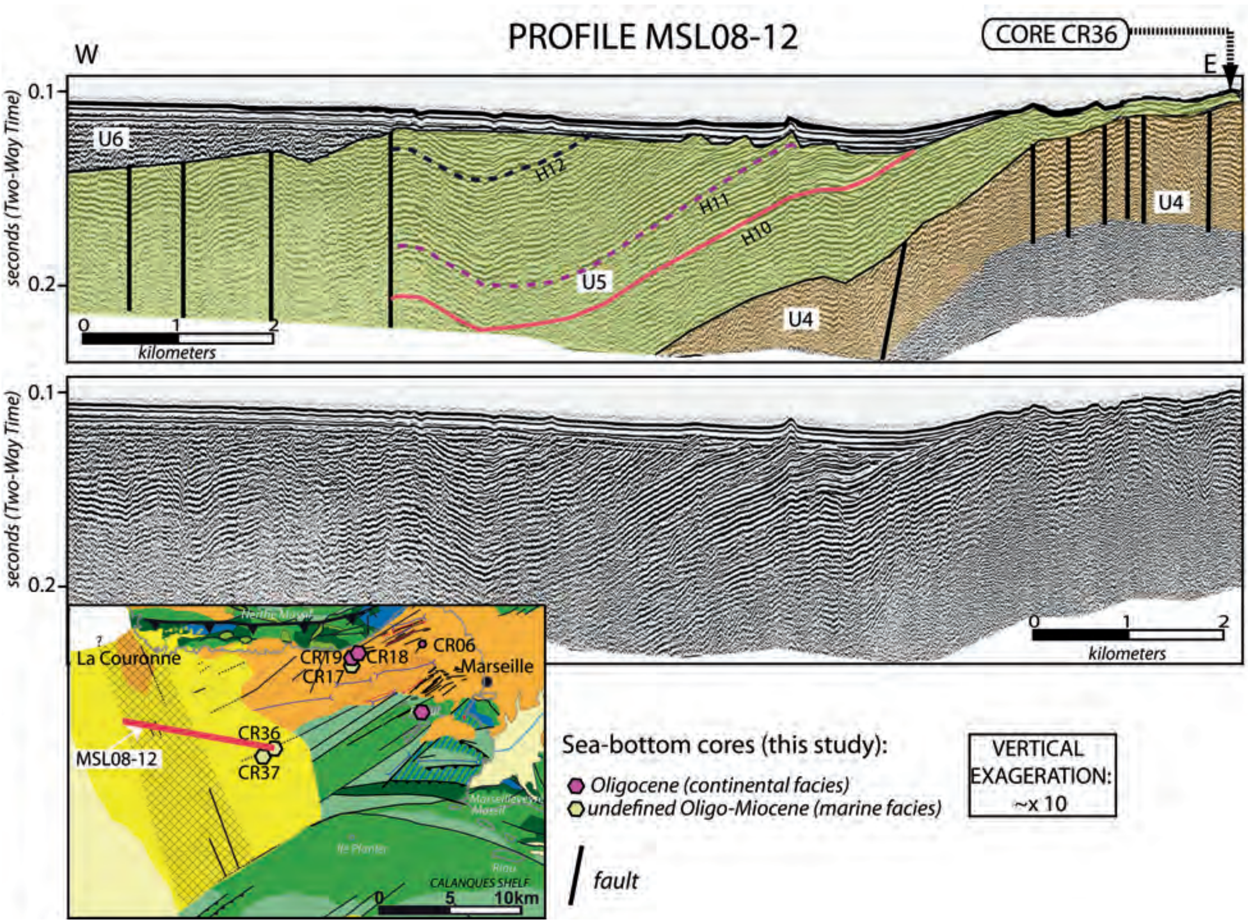


FIG. 19. – VHR sparker seismic image and interpretation of profile MSL08-12, located west of the bay of Marseille (see location in fig. 1 and 21). U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

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 extension (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.

FIG. 18. – VHR sparker seismic image and interpretation of profile MSL08-14, located south of La Couronne (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.

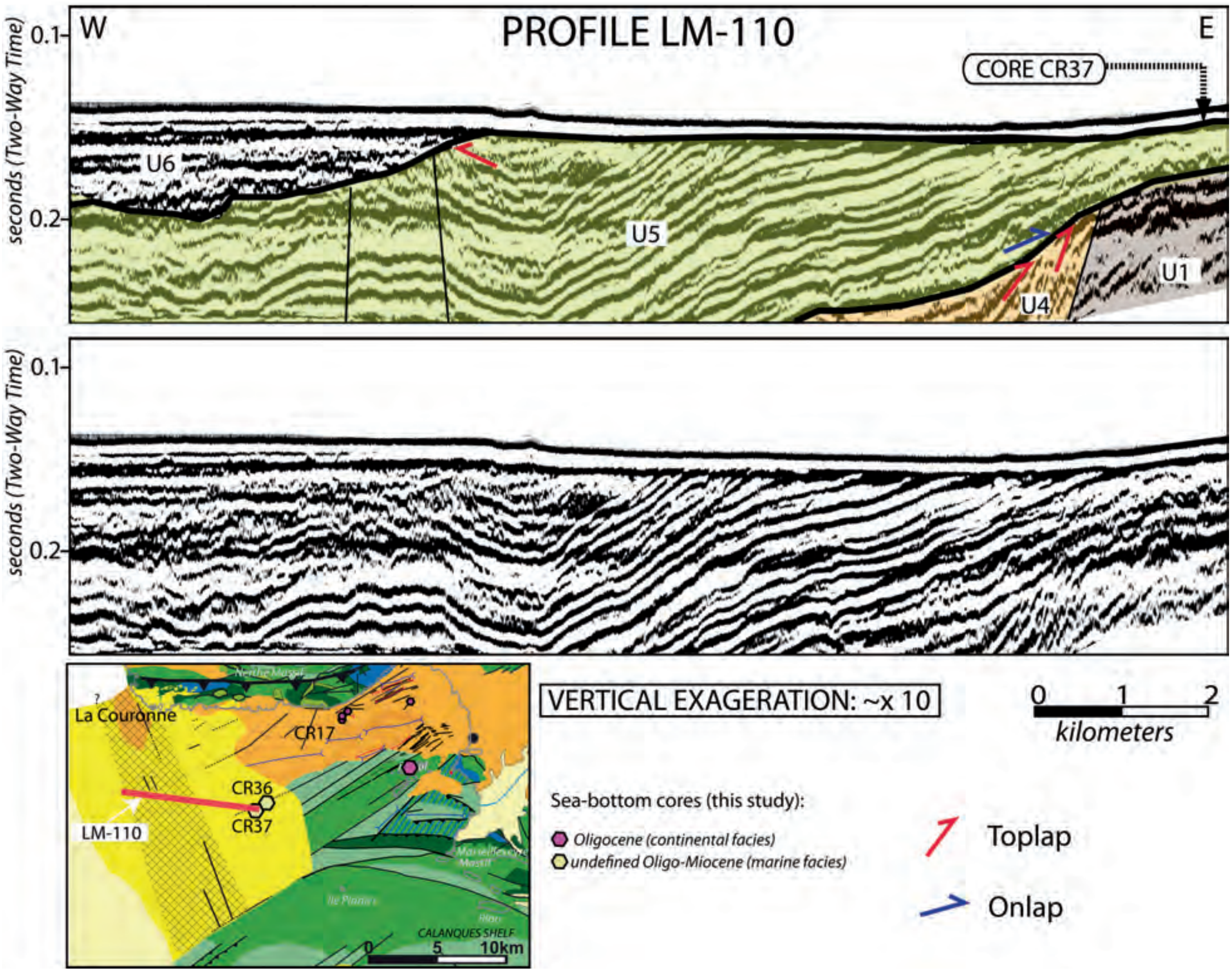


FIG. 20. – HR airgun seismic image and interpretation of profile LM110, located west of the Bay of Marseille (see location in fig. 1 and 21). U1: Aptian-Albian; U4: syn-rift to early post-rift (Chattian to early Burdigalian); U5: post-rift (mid-Burdigalian to Messinian); U6: Plio-Quaternary.

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 overly the Urgonian limestone (top of unit U0) and the unconformable contact between

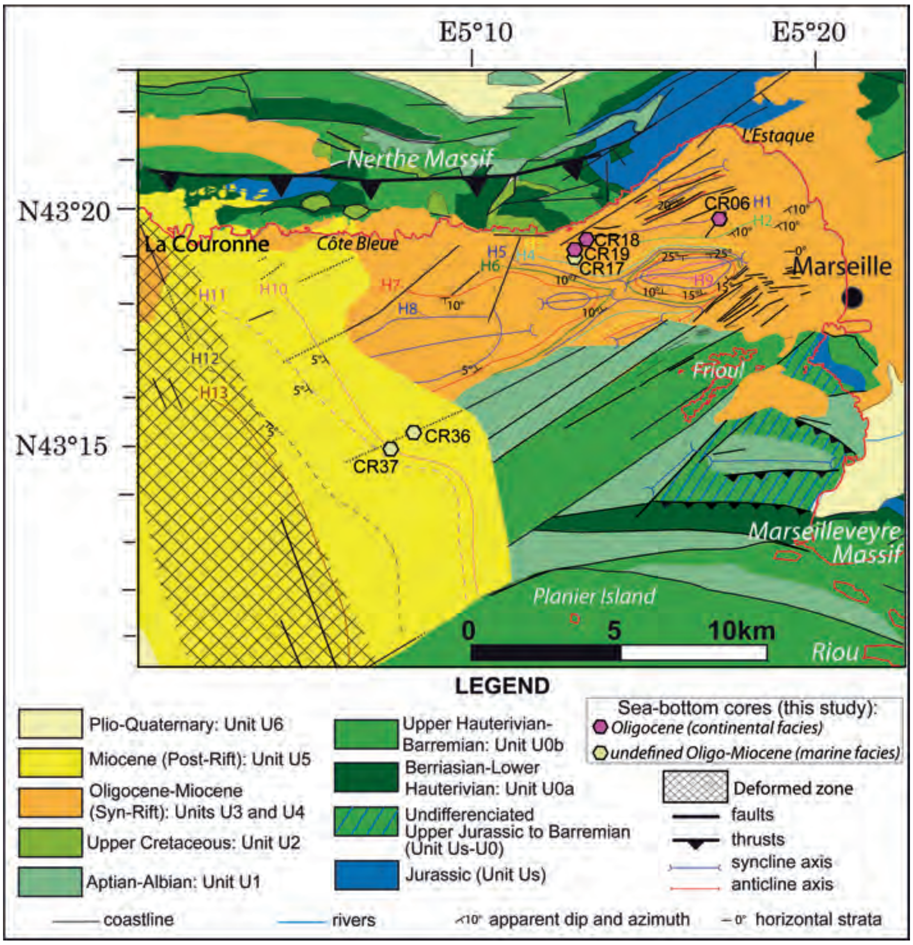


FIG. 21. – Offshore geological map of the bay of Marseille with location of the seismic profiles figured in the present paper. H1 to H13: intersection of selected seismic horizons with the sea bottom.

Aptian marls and overlying Cenomanian quartzone 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 TWT) 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 Durancian 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 TWT). 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 relict 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 nannofossil 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

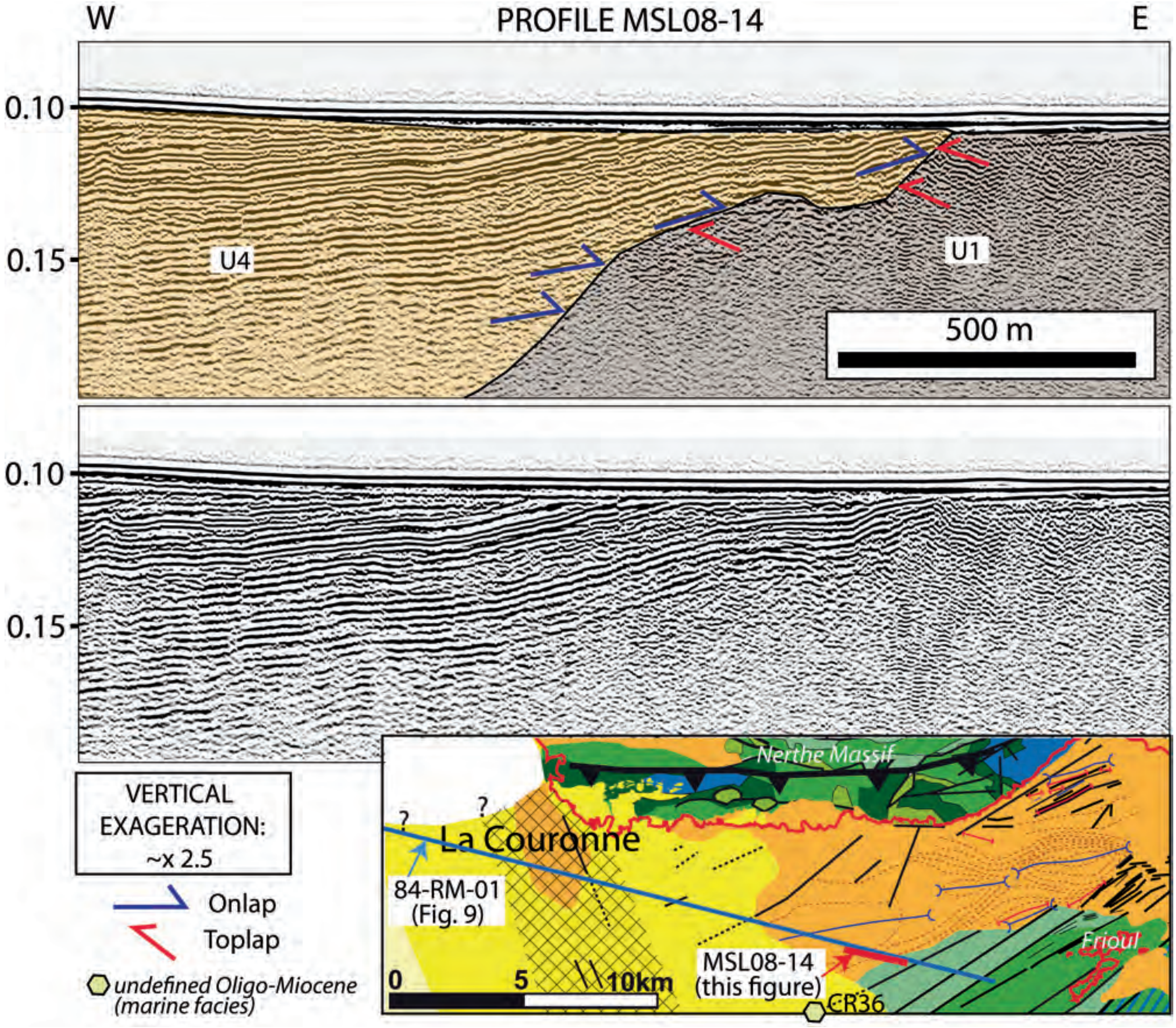


FIG. 22. – VHR sparker seismic image and interpretation of profile MSL08-14, located on the southern margin of the Oligo-Miocene Marseille extensional basin (see location in fig. 1 and 21). U1: Aptian-Albian; U4: syn-rift to early post-rift (Chattian to early Burdigalian).

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

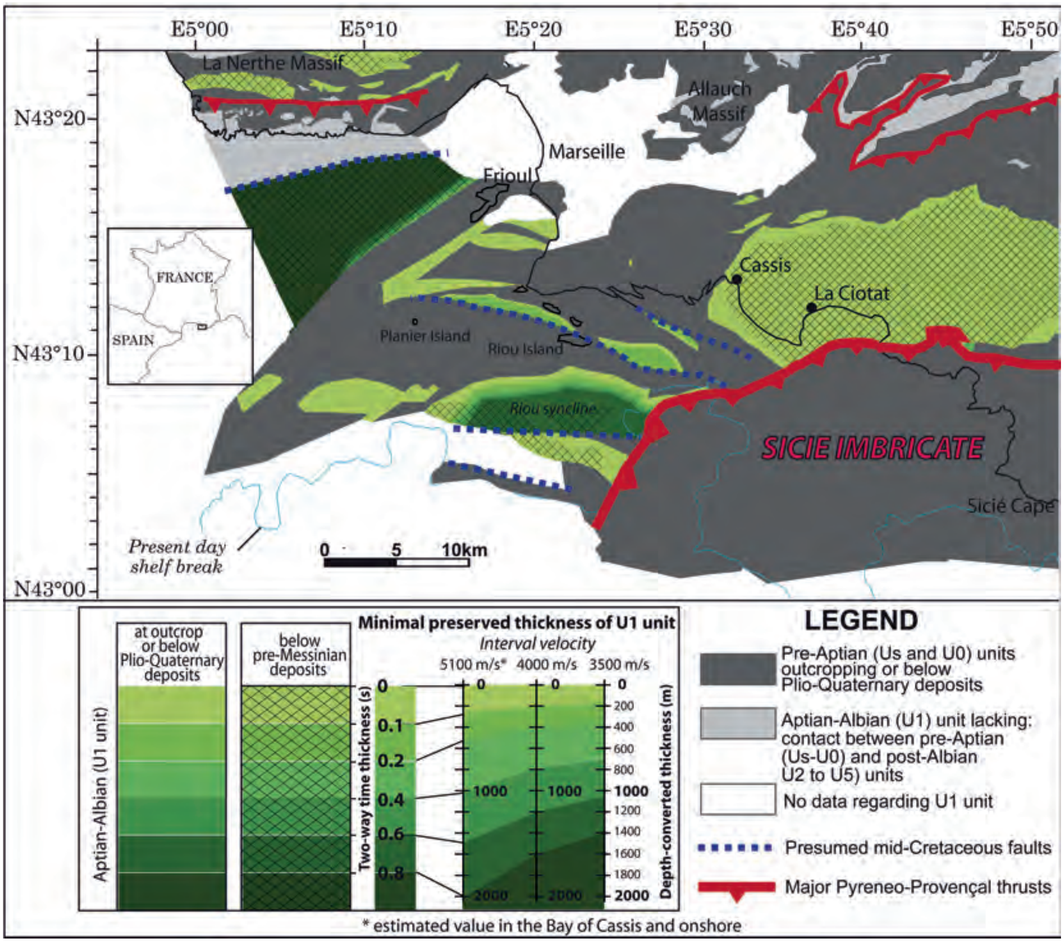


FIG. 23. – Onshore and offshore occurrence and thickness of Aptian-Albian deposits with indication of presumed mid-Cretaceous faults and major Pyreneo-Provençal thrusts.

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 Sicié 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:

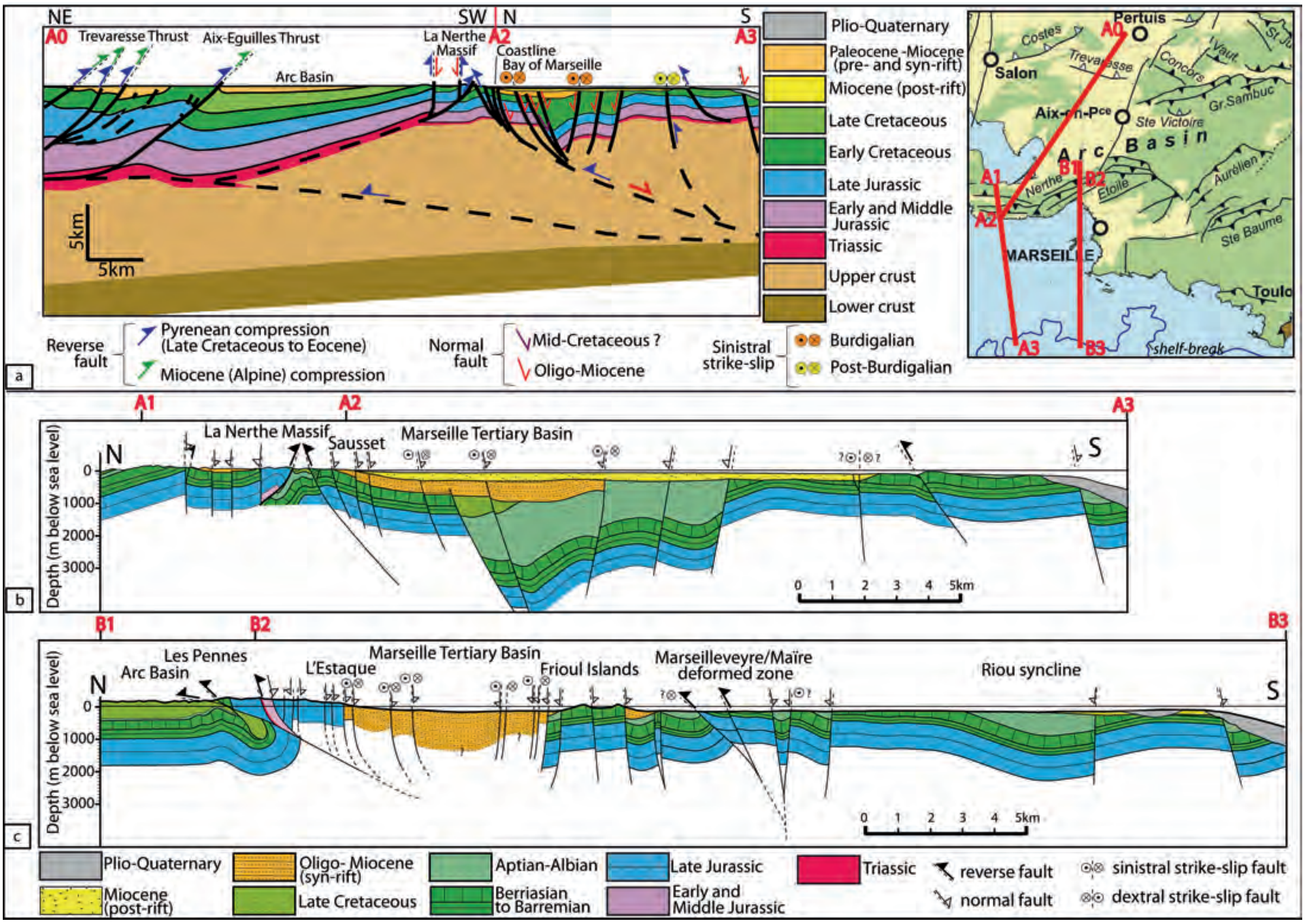


FIG. 24. – a) Interpretative crustal-scale cross section summarizing the in-depth interpretations of the southern Provence area; onshore structures and interpretations are compiled from Lacombe and Jolivet [2005], Terrier *et al*. [2008], Molliex *et al*. [2011] and Andreani *et al*. [2013]. b) Geological cross-section across the Nerthe range onshore (modified from Andreani et al. [2013]) and the Provence continental shelf offshore (from the present database). c) Geological cross-section across the western Etoile range onshore (modified from Andreani *et al*. [2010]) and the Provence continental shelf offshore (from the present database). For b) and c) detailed location is shown on figure 2.

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.

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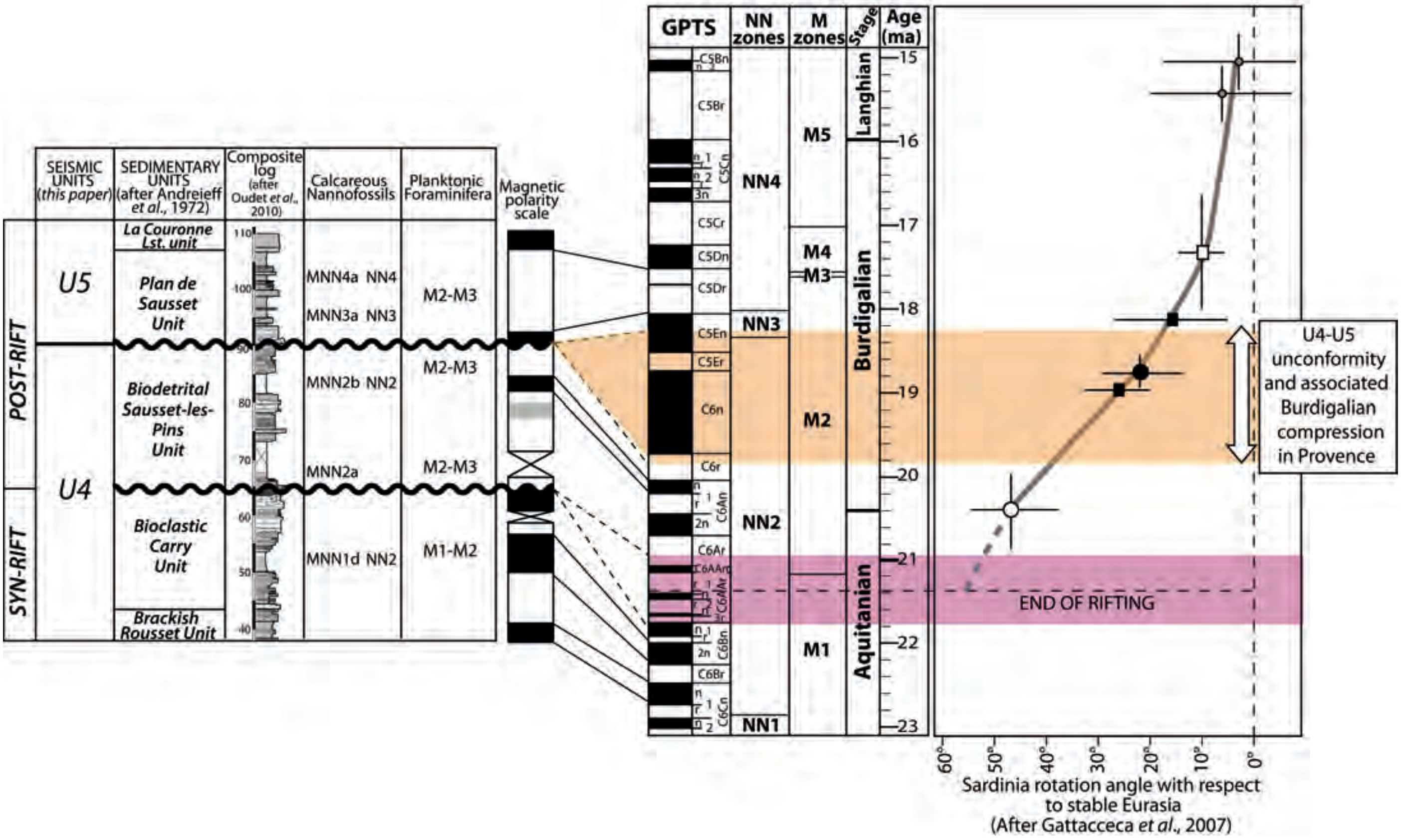

FIG. 25. – Chronostratigraphic constraints of the U4 (syn-rift to early post-rift) and U5 (later post-rift). Such chronostratigraphic framework is compared with the evolution of the Liguro-Provençal basin and associated rotation of Sardinia with respect to stable Eurasia [after Gattacceca *et al.*, 2007].

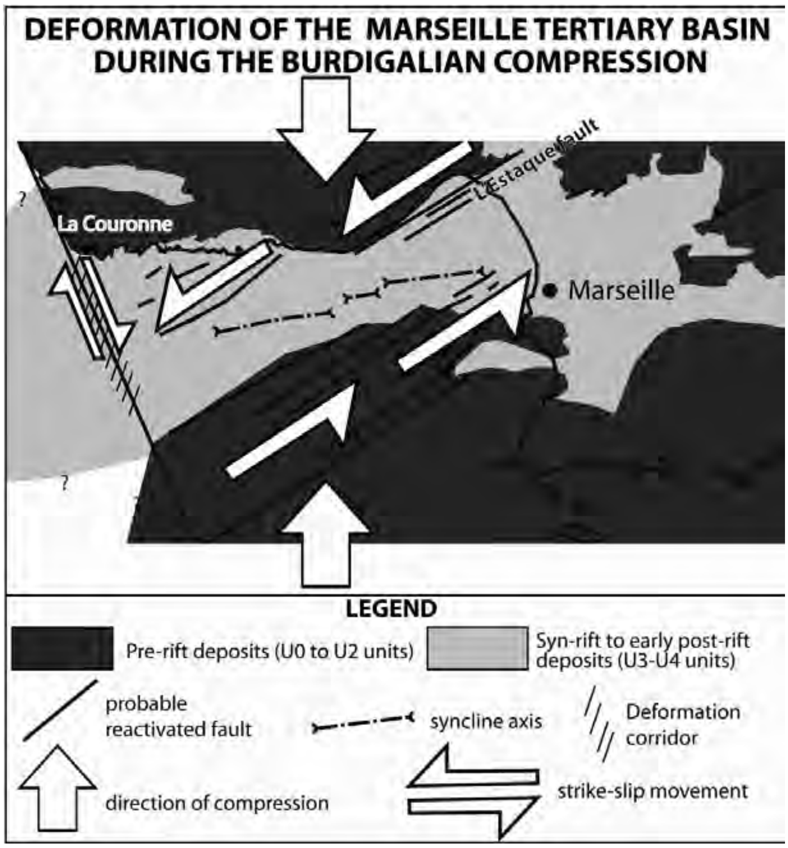

FIG. 26. – Sketch of the deformation of the Tertiary Marseille basin during the Burdigalian compression.

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