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Comments on the paper entitled : "New structural constraints on the southern Provence thrust belt (France) : evidences for an Eocene shortening event linked to the Corsica-Sardinia subduction". by LOUIS ANDREANI, NICOLAS LOGET, CLAUDE RANGIN and XAVIER LE PICHON. *Bull. Soc . géol. Fr.*, (2010), **181**, n° 6, 547-563.

Key-words.- Tectonics, Southern Provence, La Nerthe range, L'Etoile range, Paleogene, Neogene.

Abstract.- We discuss the Andreani *et al*.'s tectonic interpretation of both la Nerthe and L'Etoile ranges which form the western part of the Southern-Provence thrust defined by Aubouin & Chorowicz (1967). Referring to previous works, emphasis is given to the structural independence of the two ranges. The Western L'Etoile range is underthrusted beneath the Southern La Nerthe tectonic unit along the Graffiane key-area aptian corridor.
In contrast with the autochthonous concept of La Nerthe range by Andreani *et al*., structural and paleogeographic data are presented, supporting the interpretation of the southern part of the range as an important north-verging thrust emplaced during the Bartonian major tectonic event. This one was followed by a shortening Ludian (Priabonian) event resulting in a strong refolding of the southern La Nerthe structures.
Contrary to the Andreani *et al*'s interpretation, field facts provide evidence that the WE-trending fault systems affecting La Nerthe and L'Etoile ranges have formed during the NS-distensive regime that started from early Rupelian and that was accentuated during late Chattian and Aquitanian.
However, stratigraphical and tectonic regional data suggest a Middle Oligocene strike-slip reactivation of the WE-trending system faults of La Nerthe range, coeval to north-verging overthrusting and reverse faulting, affecting early Oligocene formations of the neighbouring Marseilles basin.

Observations sur la note intitulée : « Nouvelles contraintes structurales sur la ceinture de plis de la Provence méridionale (France) : arguments en faveur d'un raccourcissement Eocène lié à la subduction corso-sarde ».

Mots-clés.- Tectonique, Provence méridionale, chaîne de la Nerthe, chaîne de l'Etoile, Paléogène, Néogène.

Résumé. - Nous discutons dans cette note l'interprétation tectonique d'Andreani *et al*. des chaînes de l'Etoile et de La Nerthe qui constituent la partie occidentale du chevauchement Sud-provençal défini par Aubouin et Chorowicz (1967). En référence à des travaux antérieurs, nous soulignons l'indépendance structurale des deux chaînes. La partie occidentale de la chaîne de l'Etoile est chevauchée par la Nerthe méridionale le long du couloir aptien de Graffiane, apparaissant ici comme un secteur tectonique-clé. Contrastant avec le concept autochtoniste de la Nerthe développé par Andreani *et al*., nous montrons que les données structurales et paléogéographiques sont en faveur de l'existence d'un important chevauchement à vergence nord dans la partie méridionale de la Nerthe, mis en place pendant la phase pyrénéo provençale majeure (Bartonien). Ce chevauchement fut suivi d'un événement compressif daté du Ludien (Priabonien) qui a replissé les structures de la partie méridionale du massif de la Nerthe.
Contrairement à l'interprétation d'Andreani *et al.,* les données de terrain conduisent à considérer le système de failles WE qui affectent la Nerthe et l'Etoile, comme s'étant formé dans un régime distensif

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NS, initié au Rupélien inférieur et qui s'est accentué au Chattien supérieur et durant l'Aquitanien.
Les données stratigraphiques et tectoniques régionales suggèrent cependant à l'Oligocène moyen un rejeu en décrochement des accidents WE, contemporain de la formation de chevauchements à vergence nord et de failles inverses, affectant les formations de l'Oligocène inférieur du bassin de Marseille.

Introduction

The authors provide an overview of the tectonic history of the southern Provence, by re-interpreting facts previously established, using a microtectonic analysis of three structural regional units : La Nerthe range, the Western Etoile range and the Sainte-Victoire range.
Since the works from M. Bertrand [1899], the southern Provence thrust belt is regarded as formed by plurikilometers long, WE-trending, north or south-verging overthrusts related to the Pyrenean-Provence compressional event of late Middle Eocene age [the so-called Bartonian phase : Vasseur, 1898 ; Aubouin and Mennessier, 1962]. Overthrusts are interpreted as due to a major shallow décollement of the Mesozoic cover above the Triassic evaporites [Aubouin and Mennessier, 1962]. However, the hercynian basement is involved in the thrusts as shown by the Sicié overthrust [Bertrand and Zürcher, 1891; Arthaud and Seguret, 1981]. According to Tempier [1987] and Lacombe and Jolivet [2005] the basement would also be involved in La Nerthe and Sainte-Victoire overthrusts. As referred by paleostress analyses, the southern Provence overthrusts would result from a nearly N-S compression during the major Bartonian phase [Lacombe and Jolivet, 2005]. But, the shortening amount of the sedimentary cover was debated : 60 km [Guieu and Rousset, 1978] *vs* 25 km [Tempier, 1987].
New studies in La Nerthe and L'Etoile ranges are of particular interest in the debate relative to the tectonic of the southern Provence belt, due to their vicinity to the Eocene-Oligocene Arc basin and to the Oligocene Marseilles and Saint-Pierre basins. Moreover, the conclusions of the last synthetic tectonic work on L'Etoile et La Nerthe ranges [Guieu, 1977] are challenged by the Andreani *et al*. paper. Indeed, these authors provide new interpretations about the structure of La Nerthe and L'Etoile overthrusts and on the age and the direction of the compressional constraints. In the present paper we consequently will focus our comments on these two ranges and we will discuss the value of the new interpretations by taking into account the stratigraphical and tectonic works carried out in this region during last decades.

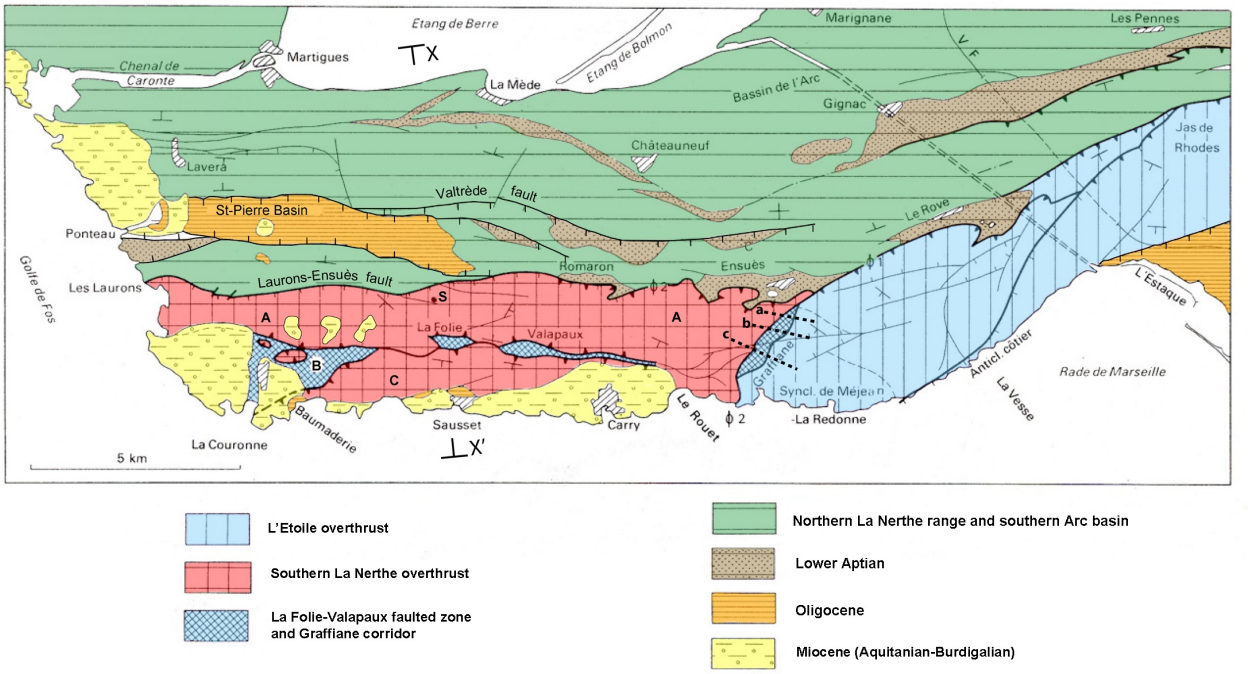

Fig. 1- Geological and structural map of La Nerthe range and Western L'Etoile range (after Guieu 1977, modified). A : Chapats unit- B : La Couronne unit- C : Sausset unit- S : La Folie borehole- a,b,c : location of sections on Fig. 2 - XX' location of the section Fig. 3.
Fig. 1- Carte géologique et structurale du massif de La Nerthe et de la partie occidentale du massif de L'Étoile (d'après Guieu, 1977, modifié). A. Unité des Chapats- B. Unité de la Couronne- C. Unité de Sausset- S. Forage de La Folie- a,b, c : localisation des coupes sur la Fig. 2- XX' Localisation de la coupe Fig. 3.

1. Distinction between La Nerthe range and L'Etoile range.

Both La Nerthe and L'Etoile ranges correspond to the western part of the major EW-trending « *Southern-Provence thrust* » as defined by Aubouin and Chorowicz [1967].
La Nerthe range lies along the southern margin of the Etang-de-Berre Late Cretaceous syncline, while L'Etoile range is a north-verging thrust emplaced over the Late Cretaceous-Eocene Arc basin. According to Andreani *et al.* (p. 550, fig. 3) the EW-trending La Nerthe range connects progressively eastward to the NE-SW-trending L'Etoile range. In this viewpoint, no structural boundary lies between the two tectonic units.
However, in our opinion, the *sensu stricto* La Nerthe range (also labelled the Martigues range) strictly relates to the EW-trending branch of the overall structure described by Andreani *et al.* The boundary between La Nerthe range and L'Etoile range lies in the Graffiane aptian corridor (fig. 1) that represents a key-tectonic area previously described in details by Guieu and Philip [1972].
The main results of this study have to be recalled (fig. 2): i) along the Graffiane corridor, the western part of l'Etoile range is underthrusted beneath the southern part of La Nerthe (Chapats) unit ; ii) the contact between the two units is laid out by Late Aptian, Albian, Cenomanian and Senonian para-autochthonous thrust slices (not referred by Andreani *et al.*) occuring in front of the Chapats unit overthrust ; iii) subsequently to the emplacing of La Nerthe overthrust, the

Graffiane corridor played as a strong flexural axis, allowing the western part of L'Etoile range to raise.

Therefore, the Graffiane corridor appears as an important tectonic boundary which allows a fundamental distinction between La Nerthe and L'Etoile ranges, due to significative differences in structure between the two overthrusts.

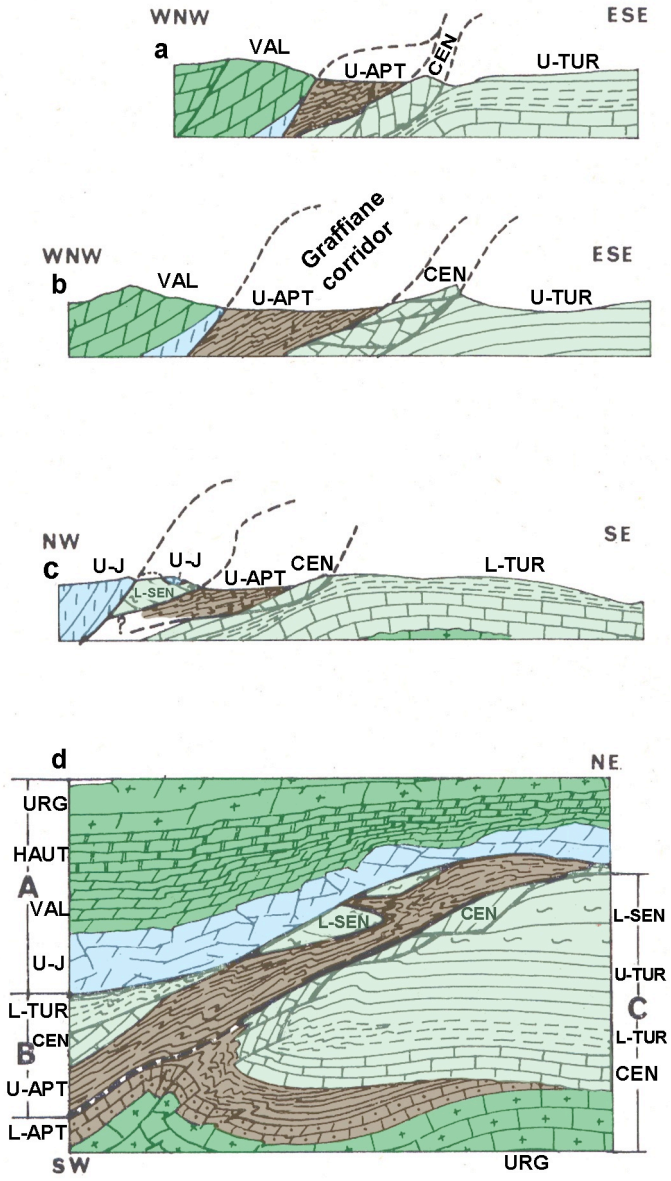

Fig. 2- Cross-sections of the Graffiane corridor (after Guieu and Philip, 1972, modified). Sections a,b, c : location on Fig. 1 ; section d : reconstruction of the Graffiane corridor before the flexural raising of the Western Etoile range.

U-J : Upper Jurassic- VAL : Valanginian- HAUT : Hauterivian- URG : Barremian (Urgonian)-L-APT : Lower Aptian- U-APT : Upper Aptian-CEN : Cenomanian-L-TUR: Lower Turonian-U-TUR: Upper Turonian-L-SEN: Lower Senonian (Coniacian-Santonian).

A : Southern La Nerthe overthrust (Chapats unit)- B : Graffiane unit - C : Western Etoile range (Méjean-La Redonne Late Cretaceous syncline).

Fig. 2- Coupes en série du couloir tectonique de Graffiane (d'après Guieu et Philip, 1972 , modifié). Coupes a, b, c, localisation Fig. 1 ; coupe d : reconstitution du couloir tectonique de Graffiane avant le soulèvement flexural de la partie occidentale du massif de l'Etoile.
U-J : Jurassique supérieur- VAL : Valanginien- HAUT : Hauterivien- URG : Barrémien (Urgonien)-L-APT : Aptien inférieur- U-APT : Aptien supérieur-CEN : Cenomanien-L-TUR: Turonien inférieur-U-TUR: Turonien supérieur -L-SEN: Senonien inférieur (Coniacian-Santonian).
A. Chevauchement de la Nerthe méridionale (unité des Chapats)- B. Unité de Graffiane- C. Partie occidentale du massif de l'Étoile (synclinal crétacé supérieur de Méjean-La Redonne).

2. Structure of La Nerthe range

Andreani *et al*. carried out a microtectonic study of the nearly WE-trending faults that affect La Nerthe range, in an attempt to infer the kinematic movements that may have occurred along these faults ; from north to south : Valtrede fault, Laurons-Ensuès fault and la Folie-Valapaux faulted zone [the so-called « la Couronne unit », Guieu 1968] (fig.1). Andreani *et al*. provided a structural interpretation of the range according to a roughly north-south trending section (p. 551, fig. 4 A-A'), but without re-mapping the given area.
The Andreani *et al*.'s study of La Folie-Valapaux faulted zone deserves particular comments.
Firstly, the northern fault that limits this zone is interpreted by these authors as a right-lateral, northward gently-dipping fault, bounding the Chapats unit from the Middle-Late Cretaceous core of La Folie-Valapaux zone.
Unfortunately, the authors did not discuss the interpretation proposed by Guieu [1973 ; 1977] and Assas [1991] who interpreted this fault as the north-verging thrust emplacing the Chapats unit over la Folie-Valapaux zone (fig. 3). It is noteworthy that the Guieu's interpretation was an alternative explanation to the subsurface structure documented by the CFP-La Folie borehole [Dufaure *et al*. 1969 ; location fig. 1].
Second, a question arises about the structural significance of the southern fault that bounds La Folie-Valapaux zone. Following the authors, this fault should be a south-dipping reverse fault rooted in the Jurassic Arc syncline basement (p. 551, fig. 4A-A').
We strongly disagree with such an interpretation. As shown by numerous authors [Lutaud, 1957 ; Aubouin and Mennessier, 1962 ; Guieu, 1968], this fault corresponds to a non-rooted, major flat or southward gently-dipping thrust contact, that results in the overthrusting of the Middle Cretaceous series of La Folie-Valapaux zone by the lower Cretaceous thrust unit of the southern La Nerthe range [the so-called « Sausset unit », Guieu 1968 ; fig. 1].
In front of this thrust, there are Turonian and Senonian crushed thrust-slices [Philip, 1970] that are misinterpreted by Andreani *et al*. as related to the autochthonous cover of La Folie-Valapaux Middle-Cretaceous serie.
It is worth noticing that the complex Cretaceous series of La Folie-Valapaux faulted zone is not only sealed by the Early Miocene marine sediments as indicated by Andreani *et al*. (p. 551) but also by early Rupelian gently-folded limestones which are overlying an overturned Late-Middle Cretaceous thrust slice in La Beaumaderie area (fig.4).

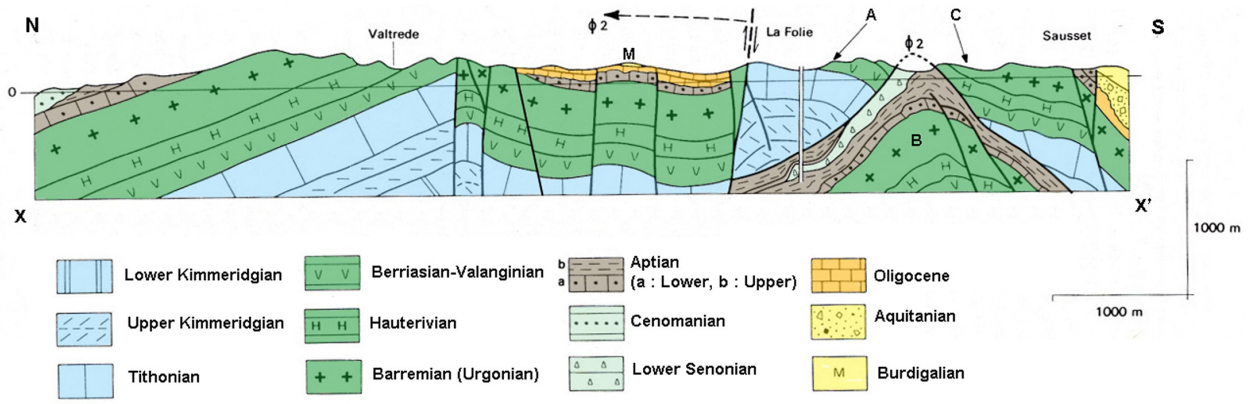

Fig. 3- Cross-section of La Nerthe range (after Guieu, 1977, modified). Location on Fig. 1 (section XX'). A. Chapats unit- B. La Folie-Valapaux faulted zone- C. Sausset unit. Φ2 : Southern La Nerthe overthrust.
Fig. 3 Coupe du massif de La Nerthe (d'après Guieu, 1977, modifié). Localisation Fig. 1 (coupe XX'). A. Unité des Chapats- B. Zone faillée de La Folie-Valapaux- C. Unité de Sausset.
Φ2 : chevauchement de la Nerthe méridionale

In other words, the Andreani *et al*. new interpretation corresponds to an autochthonous concept of La Nerthe range that would represent, according to the authors, the folded and faulted south-border of the Arc syncline, without significant northward or southward displacement of the different compartments. Unfortunately, the eastward motion of these compartments along the above mentioned faults, inferred by the authors as right-lateral faults, is not quantified and no discussion was presented about the relationship of these faults with the Chapats overthrusting on the Graffiane Upper Aptian corridor (fig. 2).

The Andreani *et al*.'s autochthonous concept of La Nerthe sweepingly contrasts with the allochthonous concept from Guieu [1973] for whom the southern La Nerthe overthrusts (Sausset unit+Chapats units) constitute an unique north-verging thrust system, subsequently folded and then cut by normal faults. In this view, La Folie-Valapaux faulted zone is considered to be a tectonic window (fig. 3). This interpretation also takes into account the existence of the parautochthonous Upper Cretaceous thrust slices, isopic to the L'Etoile range Upper Cretaceous Méjean-La Redonne series (location fig.1).
The Andréani *et al*.' s study does not take into account these structural and palaeogeographic data and minimizes the role of the Sausset thrust sheet.

3. Age and kinematics of La Nerthe WE-trending faults.

The microstructural study allows Andreani *et al*. to interpret La Nerthe range as a right-lateral transpressive flower structure. According to them, the structural data collected along the WE-trending faults of the range argue for a NW-SE shortening direction attributed by Andreani *et al*. (p. 552) to the Eocene (Bartonian) major tectonic event. A similar shortening direction would also exist in the western part of L'Etoile range and in the northern part of the Sainte-Victoire range. Moreover, the right-lateral strike-slip faults of La Nerthe range would be coeval with the NW-verging thrusting event of the western part of L'Etoile range.
However, there is no convincing evidence of a late Middle-Eocene (Bartonian) right-lateral motion along the WE-trending faults of La Nerthe range.

First, the subsequent, nearly WE anticline structure of La Folie-Valapaux faulted zone (fig. 3) implies a strong folding, then an erosion, of la Nerthe range, after the emplacing of the southern overthrust and prior to the deposit of early Rupelian limestones (fig. 4). Fault-slip data were mainly collected by Andreani *et al*. in the Chapats unit, along La Folie-Valapaux faulted zone. According to them, many N080° to N110°-trending fault planes display right-lateral subhorizontal motion. Besides, we have measured N050° horizontal striae in the Late Cretaceous series of La Folie-Valapaux zone near la Baumaderie area.
In our opinion, the shortening event resulting in folding and perhaps strike-slip movements along La Folie-Valapaux faulted zone has occurred belatedly during a stratigraphic interval bracketted by the Bartonian emplacing of the southern overthrusting structures and by the first step of early Rupelian deposits. Therefore, this significative morpho-tectonic evolution of La Nerthe range, has probably occurred during Ludian (Priabonian) times.

Second, we consider the Ponteau, Laurons-Ensuès and Valtrede, WE-trending faults systems to have been formed subsequently to the deposit of early Rupelian series [Nury, 1988] which transgressively overlie the northern Lower-Cretaceous autochthonous compartment of the range (Saint-Pierre syncline and neighbouring areas). Indeed, by contrast with the Andreani *et al*. interpretation (p. 551, fig. 4 A-A'), it is worth to precise that the early Rupelian limestones are tilted or reversed along the Ponteau WE-trending fault limiting to the south the Saint-Pierre Oligocene syncline. Moreover, the Valtrede WE-trending fault system acted as synsedimentary normal faults during the deposit of late Oligocene syn-rift coarse breccias and olistoliths filling the northern part of the Saint-Pierre syncline [Nury, 1988]. The fault-planes do not display any mark of horizontal striae.
As a result of these data, it seems irrelevant to consider the shortening direction inferred by Andreani *et al*. from microtectonic data as having resulted in the formation of the WE-trending faults of northern La Nerthe range. These faults are linked to the NS-distensive regime that started from early Rupelian and that was accentuated during late Chattian, leading to the formation of syn-rift continental and shallow marine deposits along the southern border (« *Carry basin*») of the range [Oudet *et al*. 2010].
It is noticed that the post-rift Burdigalian horizontal deposits unconformably overlie the early Rupelian SSW dipping strata in La Beaumaderie area (fig. 4) and seal the various faults and tectonic compartments of La Nerthe range (fig. 1).

Thirdly, the horizontal striae recorded by Andreani *et al*. along the Valtrede (2 sites) and Les Laurons (1 site) WE-trending faults could be interpreted as a strike-slip motion due to the reactivation of southern thrusting structures during middle Oligocene times as it is revealed by tilting and slightly folding that affects the early Rupelian limestones and the thrust slices of « La Couronne » compartment in La Baumaderie area (fig. 4).

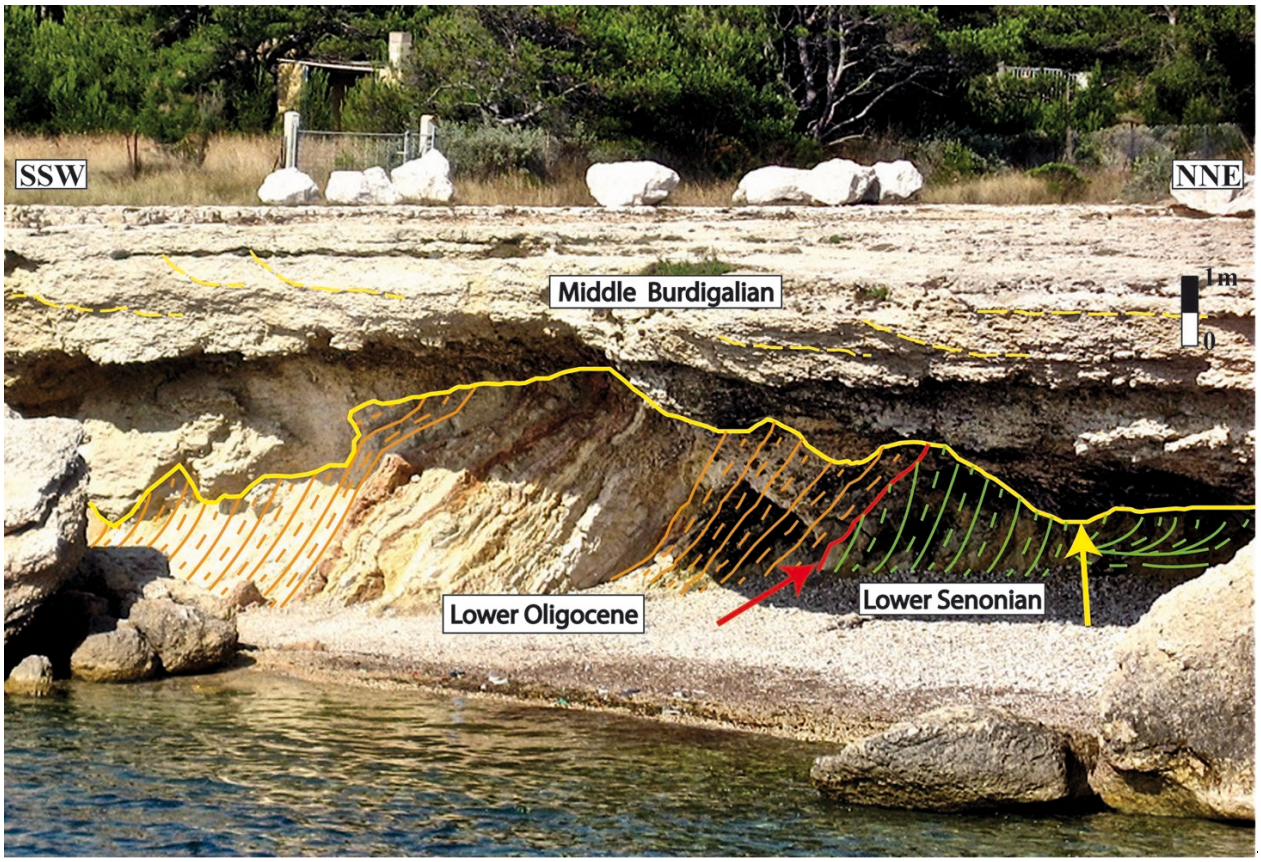

Fig. 4 Structure of the Southern La Nerthe range at La Baumaderie (location Fig. 1). The red arrow points out the angular unconformity between the underlying Lower Senonian folded marls of La Folie-Valapaux Faulted Zone and the overlying SSW dipping Lower Oligocene (Rupelian) lacustrine limestones. An erosional surface (yellow line) bounds the unconformably transgressive Middle-Burdigalian bioclastic limestones from the substrate.
Fig. 4.- Structure de la partie méridionale du massif de la Nerthe à la Baumaderie (localisation Fig. 1). Noter la discontinuité stratigraphique (flèche rouge) entre les calcaires lacustres de l'Oligocéne inférieur (Rupélien) et les marnes du Sénonien inférieur de la Zone faillée de la Folie-Valapaux. Une surface érosive (ligne jaune) délimite les calcaires bioclastiques transgressifs et discordants du Burdigalien Moyen de leur substratum.

Such a shortening event, already suggested by Nury [1972] and Guieu [1973], is consistent with the roughly north-verging overthrusts and reverse south-dipping faults, affecting early Rupelian limestones, which have been documented in the southern border of the Marseilles basin [Guieu, 1968 ; Weydert and Nury, 1978]. Moreover, NS and N 140 shortening directions have been recorded in the early Rupelian limestones filling the Marseilles basin [Nury and Raynaud, 1986]. Whereas the authors have attributed these different directions to alpine shortening stages [Nury and Raynaud, 1986 ; Hippolyte *et al.*, 1991] a middle-Oligocene transpressive strike-slip reactivation of late Middle Eocene (Bartonian) major structures cannot however be excluded.

Referring to the eastern Languedoc, it is noteworthy that this region is considered to have undergone an overall extensional regime since the Ludian times [Cavelier, 1984 ; Sanchis and Séranne, 2000]. However, a compressional early-middle Oligocene event, affecting middle

Ludian strata, was mentioned by Philip *et al*. [1978] in the Saint-Martin-de-Londres basin in front of the Pic Saint-Loup north-verging thrust. This local compressive event (a reactivation of the Pic Saint-Loup overthrust ?) preceded the whole NW-SE- distensive regime which prevailed in this region during late Oligocene (Chattian). Likewise, Roca *et al*. [1999] dealing with the tectonic evolution of the central Catalan margin have mentioned Eocene-middle Oligocene compressional regime and a late Oligocene extensional one in this region.

Conclusion

La Nerthe range appears as a multistage tectonic puzzle, marked by the existence of a major north-verging overthrust probably occurring during the late Middle-Eocene shortening event, followed by an early Rupelian transgression and finally affected by a complex episode of faulting prior to the Burdigalian transgression.
The Andreani *et al*.'s microtectonic data do not significantly alter this tectogenetic model but question the age and origin of horizontal strike-slip motions recorded by these authors along WE-trending fault-systems in both La Nerthe and L'Etoile ranges and referred by these authors as linked to the major Eocene (Bartonian) compressional event. However, stratigraphical and tectonic regional data suggest a shortening event during Ludian (Priabonian) times, resulting mainly in a strong folding of the southern La Nerthe range, then a Middle Oligocene strike-slip reactivation of the WE-trending system faults of La Nerthe range, coeval to the formation of north-verging overthrusts and reverse south-dipping faults, affecting early Oligocene sedimentary units of the Marseilles basin.

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