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Geodinamica Acta

ISSN: 0985-3111 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/tgda20

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To cite this article: A. Michard & G. Martinotti (2002) The Eocene unconformity of the Briançonnais domain in the French—Italian Alps, revisited (Marguareis massif, Cuneo); a hint for a Late Cretaceous—Middle Eocene frontal bulge setting, Geodinamica Acta, 15:5-6, 289-301, DOI: 10.1080/09853111.2002.10510762

To link to this article: http://dx.doi.org/10.1080/09853111.2002.10510762

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Geodinamica Acta 15 (2002) 289–301

Geodinamica Acta

www.elsevier.com/locate/geoact

Original article

The Eocene unconformity of the Briançonnais domain in the French–Italian Alps, revisited (Marguareis massif, Cuneo); a hint for a Late Cretaceous–Middle Eocene frontal bulge setting

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Abstract

The tectonic significance of the Eocene unconformity in the Briançonnais domain, classically regarded as recording a compressional event, is re-evaluated, based on field studies in the Marguareis massif, Maritime–Ligurian Alps. In this external, weakly metamorphic Briançonnais unit, we describe N-trending, folded paleo-normal faults. These paleofaults operated during the Late Cretaceous–Late Eocene, and control both the thickness of the Senonian–Paleocene calcschists and the distribution of the disconformable Middle Eocene–Early Priabonian formations, i.e. the channelised, resedimented Nummulitic limestones, associated with sandy turbidites, and the sandy-calcareous Lower Flysch Noir. The chaotic Upper Flysch Noir (Priabonian), which includes olistoliths from the Helminthoid Flysch nappes, disconformably overlies the Late Cretaceous–Middle/Late Eocene levels. At the scale of the whole Briançonnais domain of the French–Italian Alps, the superimposed Senonian–Eocene disconformities would indicate extensional faulting and block tilting, associated with a regional uplift which caused emersion of part of the domain (most internal Briançonnais, Corsica). Extension and coeval uplift would record the crossing of the frontal flexure (external bulge) of the European/Briançonnais lower plate situated west of the Alpine subduction zone between 80–70 Ma and ~40 Ma, i.e. before the subduction of the Briançonnais plateau around 38–35 Ma.

Keywords: Unconformity; Paleofaults; Subduction; Frontal bulge; Western Alps; Corsica

1. Introduction

The idea that unconformities record folding events (i.e. compressional phases), subaerial erosion and subsequent onlap of shallow water deposits is one of the oldest, basic geological concepts. In the internal part of the Helvetic–Dauphinois External Zones of the western Alps (Fig. 1A), an unconformity at the bottom of the "Nummulitic trilogy" (calcarenites, marls, flysch) was previously observed sealing "Pyrenean–Provençal" folds [1–3]. The occurrence of roughly similar and partly coeval sediments (Nummulitic "Flysch Noir") in the more internal, Subbriançonnais and Briançonnais domains was regarded as also recording coeval shortening there (cf. the concepts of "cordillère" or "nappe embryonnaire" [4] and "Meso–Alpine phase" [5]). In the Maritime–Ligurian part of the Briançonnais domain, the occurrence of thick (up to 50 m), nummulite-rich limestones was taken as evidence of a shallow water onlap after a tectonic event, viewed as being of compressional or transpressional nature [6–8].

On the other hand, modern geology emphasised the importance of extensional tectonics, both during rifting and drifting in the future Alpine orogen [9–11], and during its further, synorogenic evolution within the subduction wedge/orogenic prism, accounting for the exhumation of high-pressure, low-temperature metamorphic rocks [12–15]. Yet, another site of synconvergence extension occurs in the frontal flexure (also referred to as external bulge or outer high) of many active subduction zones [16,17]. The occurrence of flexural forebulge unconformities and syndepositional normal faulting due to flexural bending stresses has been modelled in the case of the Eocene–Miocene perialpine deposits [18–20]. Conversely,

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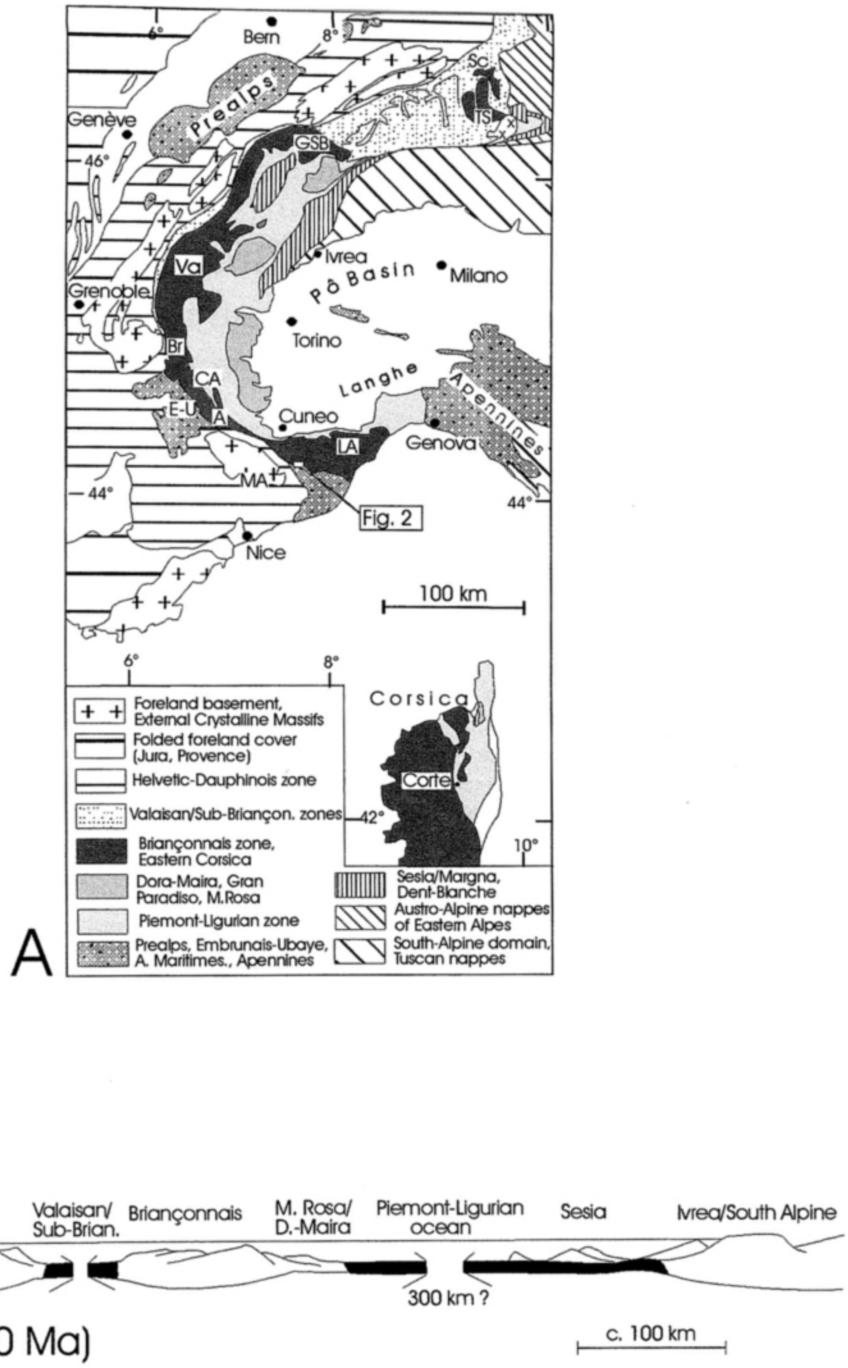

Fig. 1. The Briançonnais domain of the western/central Alps and Corsica. (A) Sketch map with location of the Marguareis massif (Fig. 2) and other cited areas (A, Acceglio; Br, Briançon; CA, Cottian Alps; E-U, Embrunais-Ubaye; GSB, Grand Saint Bernard; LA, Ligurian Alps; MA, Maritimes Alps; Sc, Schams; TS, Tambo-Suretta; Va, Vanoise). (B) Current restoration of the western Alps transect during the Early Cretaceous, after [30], [33], [74].

the external bulge has not been considered yet in the Alpine literature as a potential mechanism accounting for some pre-orogenic events in the Briançonnais domain, except for the pioneering paper by Stampfli et al. [21] (see also [22]). In their actualistic restoration of the western Alps, Stampfli et al. [21] propose a quantitative approach of the evolution of a foreland flexure linked to the Alpine (Piemont–Ligurian) subduction, but limit their study to the Swiss Alps.

In the present paper, we focus on the Late Cretaceous-Paleogene stratigraphic evolution of the Briançonnais, with emphasis on the Eocene period. The Marguareis massif of the Maritime-Ligurian Alps is taken as a case study for deciphering the significance of the Eocene unconformity in the Briançonnais of the French–Italian Alps and Corsica. Based on new field data from the Marguar is massif, and on the literature, we argue that the unconformities/

disconformities observed throughout this domain during the Early-Middle Eocene result from Late Cretaceous–Eocene extensional deformation associated with a regional uplift. These tectonic events would record the crossing of the flexural bulge by the Briançonnais before being buried in the Piemont–Ligurian subduction zone.

2. Geological setting

The Briançonnais (Middle Penninic) zone sensu stricto extends from Eastern Switzerland (Schams and Tambo-Suretta units) to the Prealps and Grand Saint Bernard transect, to the Vanoise massif, Briançon region, south Cottian Alps, and eventually to the Maritime-Ligurian Alps (Fig. 1A). South of the post-orogenic Ligurian Sea, the Briançonnais zone can be recognised (although with significant differences) in the autochthonous–parautochthonous units of Corsica [23,24]. The Mesozoic sequence of the external/median Briançonnais units [25,26], exemplified by the Marguareis-Ormea unit in the Ligurian transect [7,8], is characterised by shallow marine Triassic sediments (Scythian quartzites, Middle to Upper Triassic carbonates); a Liassic–Bajocian erosional hiatus with some bauxite deposits; transgressive, shallow water Bathonian limestones; Upper Jurassic (to Berriasian) pelagic marbles; phosphatic-manganesiferous crusts (hard-grounds) mostly dated from the Senonian, and Upper Cretaceous–Paleocene pelagic calcschists (also referred to as "calcaires en plaquettes" or "marbres chloriteux"). In the most internal Briançonnais (Ultrabriançonnais = Acceglio zone) units, the post-Early Triassic cover is virtually restricted to the Upper Jurassic and Upper Cretaceous levels [27,28]. From the Late Jurassic to the Late Cretaceous–Paleocene, the Briançonnais domain represented a submarine plateau bounded to the SE by the Upper Penninic Piemont–Ligurian ocean, and to the NW by the Lower Penninic Valaisan–Subbriançonnais ocean or trough (Fig. 1B). This Briançonnais plateau was either interpreted as a first-order tilted block (or horst) of the distal European margin [28–30], or as the northern tip of an Iberia/Briançonnais plate, separated from the European plate by the Pyrenean–Valaisan oceanic rift [21,31,32].

After the complete subduction of the Piemont–Ligurian ocean beneath the Adria leading edge due to the Adria–Europe convergence, the Briançonnais was incorporated into the Alpine orogenic prism [21,30,32–36]. The Briançonnais nappes were affected by metamorphic events, the grade of which increases from the external to the internal units. In the case of the Ligurian Alps transect, peak metamorphism occurred under low greenschist- to low blueschist-facies conditions in the external, Marguareis–Ormea nappe (Fe/Mg carpholite–chloritoid assemblages in the Jurassic meta-bauxites of the eastern part of the nappe [37]), and under deep blueschist, jadeite–quartz subfacies in the most internal units [38,39]. A second metamorphic event essentially corresponds to the retrograde evolution of the early assemblages in the latter units. In the Marguareis–Ormea case study, the syn- to post-metamorphic structures involve [40–42], (i) SW-verging, recumbent subisoclinal folds (P_1) associated with a penetrative, axial-planar foliation (S_1); (ii) N110-trending, moderately tight back-folds (P_2) associated with a strong crenulation cleavage forming centimetre-scale microlithons in calcschist lithologies; and (iii) late folds trending dominantly N130-N170 and either upright or reclined to the west (P_3–P_4). The syn- to late-metamorphic P_1 and P_2 folds occur at all scales, from some hectometres to a few millimetres, whereas the wavelength of the late- to post-metamorphic P_3–P_4 folds generally ranges from 1 dm to 1 km or more.

3. Late Cretaceous–Eocene stratigraphy of the Marguareis massif

In the centre of the Marguareis massif (Fig. 2) [8,40,43], the Plan Ambreuge area offers good outcrops of the whole Upper Cretaceous–Eocene sequence lying on top of shallow dipping Upper Jurassic limestones (Fig. 3A). Complementary data can be gained from the Col des Seigneurs and Col de Boaire–Col de la Perle synclines, which display significantly varied Eocene formations (Fig. 3B, C). The Late Cretaceous–Paleocene part of the sequence consists of the classical facies of planctonic, poorly siliceous calcschists with basal Senonian hard-grounds. The major sedimentary hiatus at the bottom of the calcschist formation is labelled hereafter the D1 discontinuity. A further discontinuity (D2 discontinuity) can be defined on top of the calcschists, as their hemipelagic, marly sedimentation is abruptly replaced upward by clastic-calcareous deposits. When complete (Fig. 3A, B), the clastic–calcareous sequence begins with a massive layer of nummulitic limestones, and ends with the so-called "Flysch Noir". On the basis of their benthic foraminifer content, the nummulitic limestones are loosely dated as late Lutetian to early Priabonian, whereas the overlying flysch is regarded as Priabonian [6,7,44]. The D2 discontinuity may be defined as a disconformity as the thickness of the underlying calcschists varies from ~300 m (Monte di Carsene) to ~10 m (eastern part of Plan Ambreuge, A1, Fig. 2).

A third stratigraphic discontinuity (D3) can be defined within the flysch sequence itself. The Lower Flysch Noir mostly consists of layered deposits (fine-grained sandy carbonates, pelites, slates) including olistostromal breccias with nummulitic limestone olistoliths (intraclasts). In contrast, the Upper Flysch Noir (above D3) dominantly consists of matrix-supported breccias with exotic olistoliths, the size of which increases upward up to a few hundred of meters. Most of these olistoliths originate from the Upper Penninic nappes of the Helminthoid Flyschs [45,46], but basaltic clasts likely reworked from the Piemont–Ligurian crust have been also described at Cima della Fascia [47]. The D3 discontinuity can be referred to again as a disconformity as,

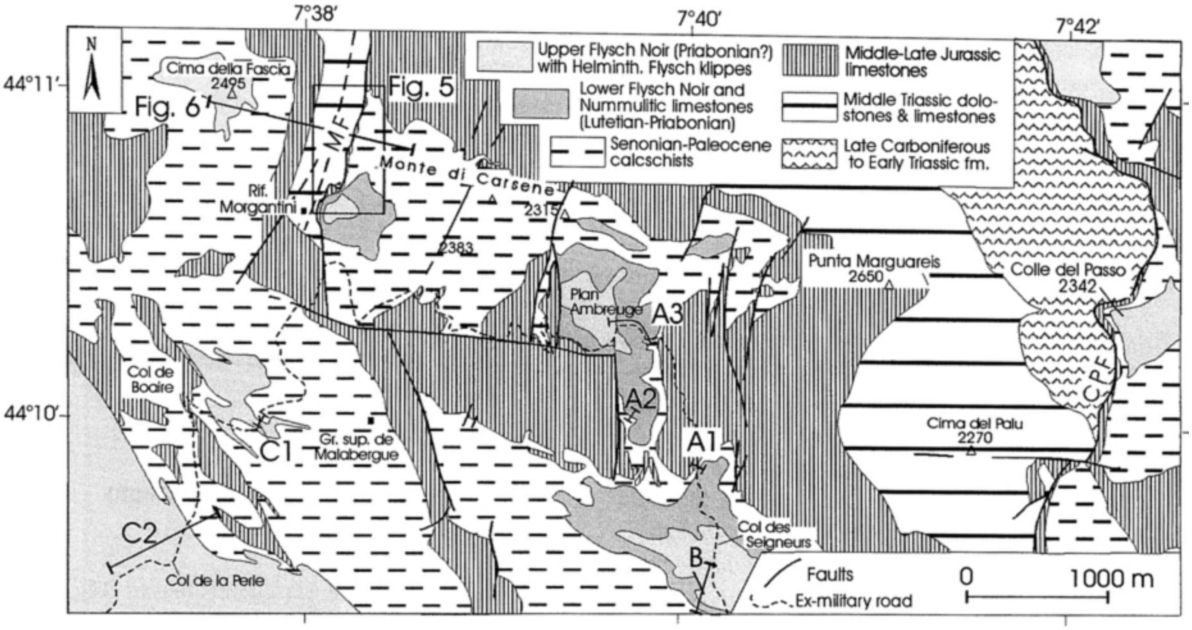

Fig. 2. Sketch map of the Marguareis massif (location: Fig. 1), after [42], [47], [50], and personal observations. MF, Morgantini fault; CPF, Colle del Passo fault. A1–A3, B, C1, C2: location of the field profiles summarised in Fig. 3. Framed: Fig. 5. Bold line across the MF: trace of the synthetic cross section Fig. 6.

in the western parts of the massif, the Upper Flysch Noir directly overlies the Upper Cretaceous calcschists (C1, C2, Figs. 2 and 3C). Therefore in the Marguareis massif, the so-called Eocene unconformity corresponds to the superposition of varied Eocene formations (nummulitic limestones or flysch deposits) on top of the Upper Cretaceous–Paleocene calcschists through two superimposed disconformities D2–D3.

It is worth noting that the nummulitic limestones above D2 do not represent shallow water deposits which would have followed an emersion (i.e. the classical interpretation), but rather consist of deep water, resedimented deposits, as hypothetically envisaged by Vanossi et al. [7]. This is supported by several observations. First, the limestones include graded sandy microbreccias (Fig. 4A) with intraclasts from the underlying calcschists, and basal load and groove casts (Fig. 4B), which suggest that sand emplacement occurred through turbidity currents. Second, the limestone-turbiditic sandstone association occurs in between two hemipelagic formations, namely the Late Cretaceous–Paleocene calcschists and the Eocene Flysch Noir. Vanossi et al. [7] noticed the occurrence of similar hemipelagic calcschist levels both beneath and above the nummulitic limestones, with *Globotruncana* and *Globorotalia* fossils, respectively. Additionally, the nummulitic limestone bodies at the very base of the Eocene sequence frequently display lenticular terminations (Fig. 4C), which suggest reworking of shallow water deposits either by channelised turbidites or by huge mass slidings. Olistoliths of nummulitic limestones clearly emplaced during the Lower Flysch Noir sedimentation (Fig. 3A, B).

4. Late Cretaceous–Eocene extensional faulting in the Marguareis massif

In this section we describe the occurrence of extensional faulting in the Marguareis area during the Late Cretaceous-Eocene, which may provide a clue to understanding the origin of the Eocene unconformity without the intervention of an emersion. Two N-trending paleo-normal faults of Late Cretaceous–Eocene age may be evidenced in the massif, i.e. the Morgantini and Colle del Passo faults (MF and CPF, Fig. 2).

The Morgantini Fault, previously referred to as Col de la Plane (Colle Piane) fault [8,45] displays a generally steep, eastward dip, and was regarded as a reverse fault [45,48], or reverse-dextral fault [8]. However, detailed mapping (Fig. 5) and synthetic cross-section (Fig. 6) show that the MF results in a downthrow of the hanging-wall (Mont de Carsene block) with respect to the footwall (Cima della Fascia block). The thickness of the calcschists close to the fault is much reduced in the uplifted block (50–80 m at Cima della Fascia) in comparison to the downthrown block (around 300 m). Moreover, the thickness of the calcschist decreases away from the fault in the downthrown block, and increases in the uplifted one (Fig. 2). This suggests that the fault operated during the calcschist sedimentation onto the faulted (and tilted) blocks (Fig. 7A). The onset of normal faulting in the Marguareis area during the Late Cretaceous is also supported by the occurrence, 1 km southeast of Rifugio Morgantini, of a metric scale normal fault in the Upper Jurassic marbles, the mirror of which is fossilised by the Senonian hard-ground crusts. However, as the MF and

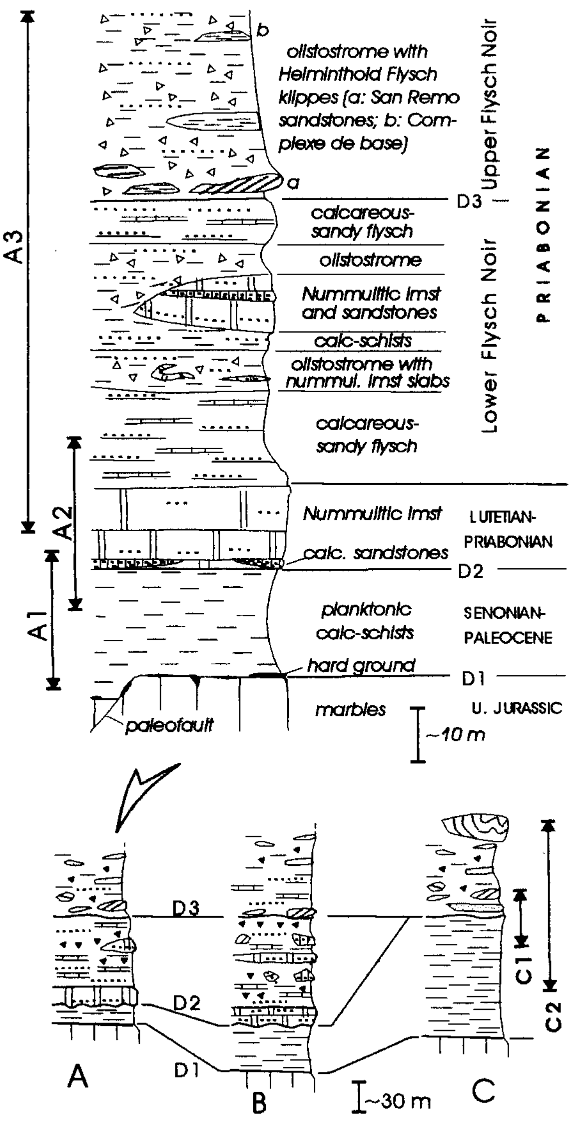

Fig. 3. Stratigraphic columns of the Late Cretaceous–Tertiary series of the Marguareis massif, based on profiles A1–A3, B, C1–C2, Fig. 2. The Plan Ambreuge sequence (A) is shown both with details (top) and simplified (below). D1–D3: superimposed disconformities (see text).

its southern extension east of the Granges supérieures de Malabergue (Fig. 2) are coincident with an Eocene stratigraphic threshold (western limit for the extension of the nummulitic limestones and Lower Flysch Noir), we speculate that the paleofault also operated during the Lutetian-early Priabonian (Fig. 7B). Scarp breccias were not observed close to the MF, but they occur in a neighbouring part of the external Briançonnais domain (Breccie della Verzera, with blocks of Triassic dolomites), and are referred to the Late Cretaceous–Early Eocene [49] or to the Middle-Late Eocene [7,43].

In the upper part of the fault close to Rifugio Morgantini, a thin Jurassic–Paleocene sequence is preserved beneath the Eocene formations. The Jurassic limestones are obliquely truncated at their base, which reveals a former low-angle, shallow-dipping fault. This paleofault was affected by two NNW-trending open anticlines and one intervening syncline (Fig. 8A), coaxial with the minor folds which affect the S_2 foliation in the calcschists, and hence corresponding to the P_3 phase. Going northward (downward), the eastern limb of the eastern antiform progressively steepens up to ca. ENE 50–60° and the Jurassic marbles thin and temporarily vanish. Still downward, two lenticular bodies of Jurassic marbles are pinched between the Triassic dolomites of the footwall and the Senonian–Paleocene calcschists of the hanging-wall. The S_2 foliation crosscuts both the calcschists and the juxtaposed, verticalised Jurassic slivers (Fig. 8B). This demonstrates that the fault operated before the P_2 event. The calcschist formation occupies the core of a P_3 synform, bounded to the west by the Triassic footwall of the

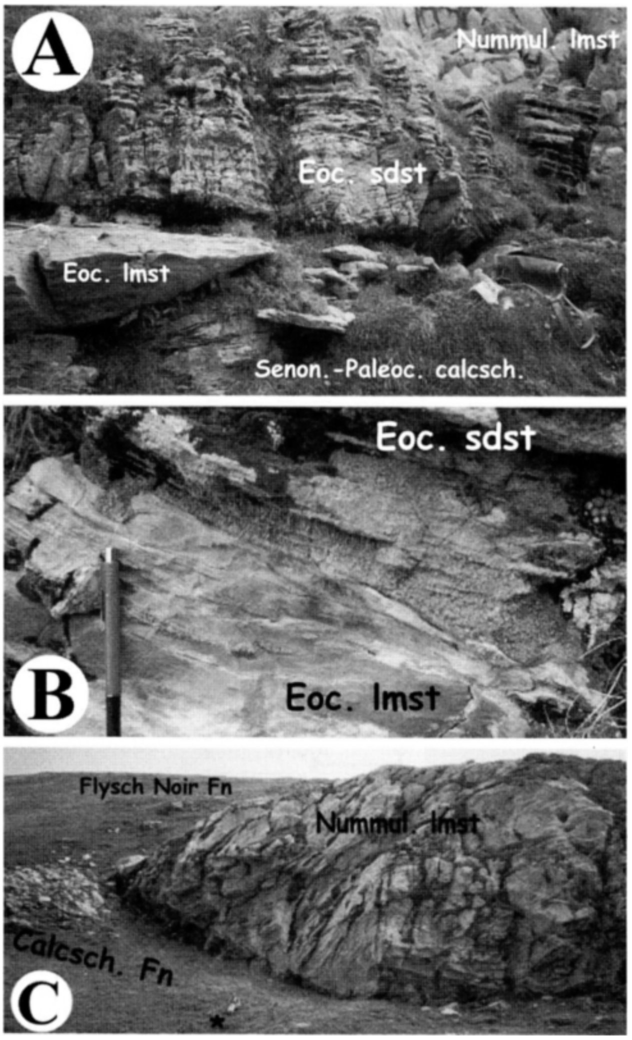

Fig. 4. The Nummulitic limestone formation in the Marguareis massif. (A) Intercalation of calcareous turbiditic sandstones (Eoc. sdst) close to the base of the formation, between some foliated sandy limestones (Eoc. lmst) and the massive Nummulitic calcarenites (Nummul. lmst); scale is given by the bag to the right. Location: A2, Fig. 2. (B) Close up at the bottom of the sandy turbidites shown in (A); sand balls and graded bedding in the lowest turbiditic layer. (C) Lensoid reworked nummulitic limestone (strongly channelised calcarenite or large lenticular olistolith?) close to the base of the Eocene sequence, 300 m NE of Rifugio Morgantini (* in Fig. 5); scale is given by the seated man near the asterisk.

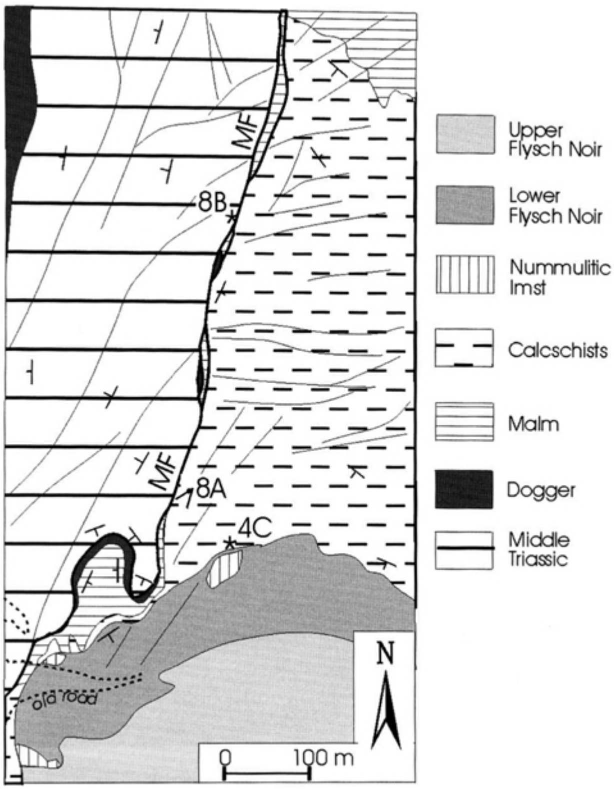

Fig. 5. Detailed map of the Morgantini fault (MF) area, based on photogeology and field observations, with location of Figs. 4C, 8A, 8B.

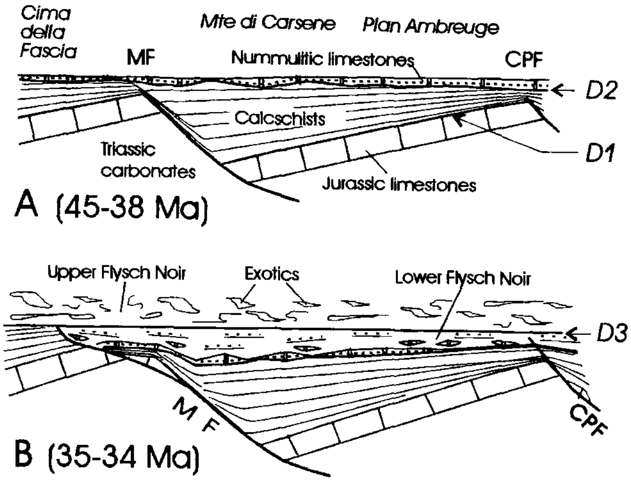

Fig. 7. Sketch illustrating the evolution of the Marguareis massif paleofaults (MF, Morgantini fault; CPF, Colle del Pas fault). (A) Cross-section of the faults and adjoining tilted blocks after the Late Cretaceous–Early Eocene extension and further disconformable Middle Eocene sedimentation. (B) Cross-section of the same blocks after the Middle Eocene-early Priabonian final extension and further olistostrome emplacement at the front of the advancing orogenic prism (late Priabonian).

fault, and to the east by a large P_3 Jurassic–Triassic antiform [42]. Some nearly vertical, post-folding faults, which control the important karstic caves in the vicinity of Rifugio Morgantini, locally affect the MF plane, and increase the dip and initial throw of the paleofault.

If correct, our interpretation predicts the occurrence of another paleofault, similar to the MF one, east of the Monte di Carsene-Plan Ambreuge paleo-tilted block (Fig. 7). As a matter of fact, such a fault occurs east of the Punta Marguareis, i.e. the E-dipping Colle del Pas fault (CPF, Fig. 2). Like the MF, the CPF was considered by Lanteaume et al. [8] as a post-folding compressional fault. However, the hanging-wall is clearly downthrown (Late Cretaceous–Tertiary outcrops) with respect to the footwall (Triassic and Permian–Carboniferous outcrops). Moreover, detailed mapping by Filippi [50] reveals the presence of Malm slivers pinched in the fault plane, similar to those observed along the MF itself. We conclude from the closely similar geometric setting of the CPF and MF that the former represents a paleofault which is coeval with the MF paleofault, and which bounded to the east (present coordinates) the uplifted shoulder of the Monte di Carsene–Marguareis block.

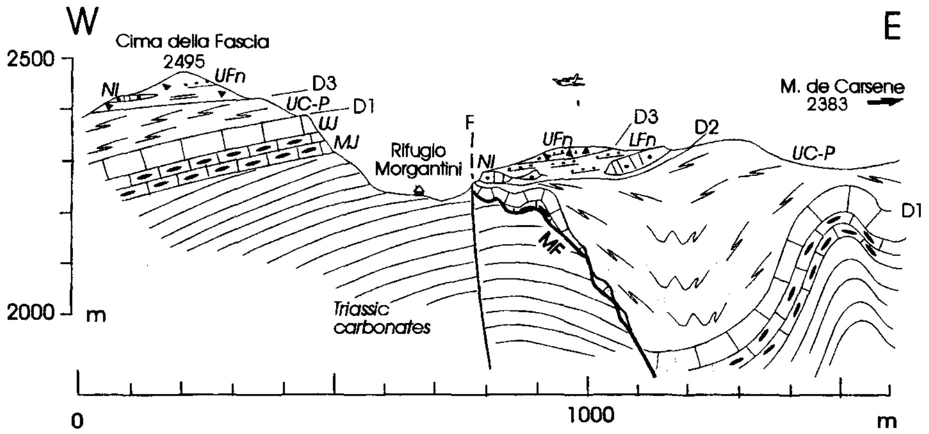

Fig. 6. Synthetic cross-section of the Morgantini paleofault (MF) and adjoining units, based on the map Fig. 5. Location: Fig. 2. UFn/LFn, Upper/Lower Flysch Noir; Nl, Nummulitic limestones; UC-P, Upper Cretaceous-Paleocene calcschists; UJ/MJ, Upper/Middle Jurassic limestones; D1–D3, disconformities as shown in Fig. 3; F, recent fault.

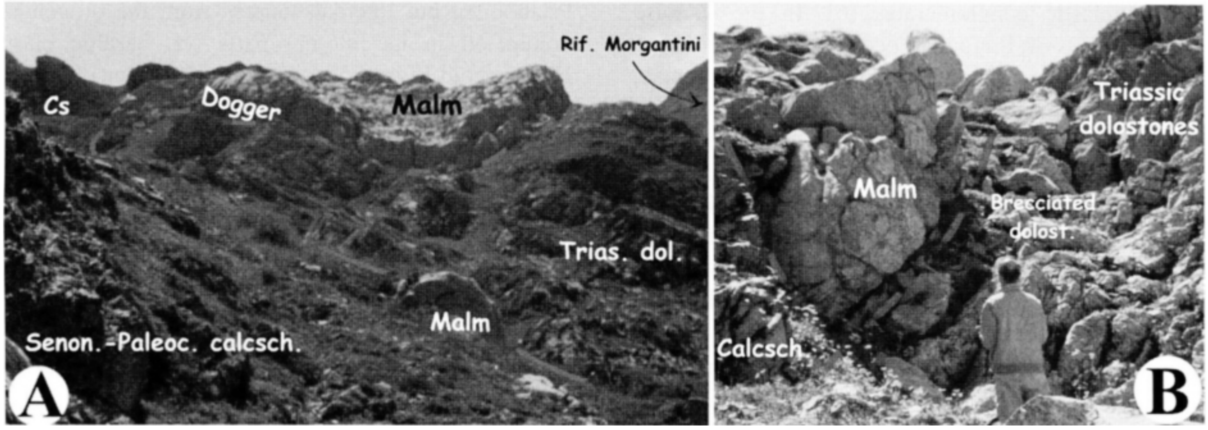

Fig. 8. Panoramic view (A) and detail (B) of the Morgantini fault (location of both views: Fig. 5). (A) Oblique view of the folded part of the fault. The hanging-wall consists of Jurassic limestones (dark limestones: upper Dogger; white marbles: Malm) overlain by the Senonian–Paleocene calcschists (Cs); the footwall is made up of Middle Triassic dolostones. (B) Close view of the northward termination of a Malm sliver pinched between the calcschists of the hanging-wall (left) and the dolostones of the footwall (right); the foliation S_3 is shown in both the calcschists and the Jurassic marbles (spaced cleavage dipping by ca. 45° to the E, i.e. to the left).

5. The Eocene unconformity in the Briançonnais realm: discussion

5.1. *Extension-related disconformities*

The salient conclusions of Sections 3 and 4 are twofold: (i) in the Briançonnais of the Marguareis massif, the Middle Eocene nummulitic limestones are resedimented deposits associated with channelised turbiditic sandstones; (ii) in the Marguareis massif, the Eocene unconformity is not a subaerial post-folding unconformity like in the Helvetic–Dauphinois domain [1–3,51], but consists of two superimposed, submarine disconformities (D2, D3) dated as Lutetian-early Priabonian and Priabonian, respectively. Like the earlier disconformity (D1) at the bottom of the Late Cretaceous–Paleocene calcschists, D2 is only related to extensional faulting and block tilting. D3 postdates the latest pre-orogenic, extensional deformation of the substrate, and is sealed by the earliest Upper Penninic nappe emplacement.

A review of the literature suggests that similar conditions prevailed everywhere in the Briançonnais domain during this period, except in its most internal and southern parts (see Section 5.2). In the Middle Penninic Préalpes Médianes [52,53], erosion and sedimentation alternated in the pelagic Couches Rouges basin (Late Cretaceous–Early Eocene), and the disconformable upper Couches Rouges (Early Eocene) begin with submarine breccias. The overlying Middle–Upper Eocene flysch itself begins with calcareous sandstones including reworked nummulites and *Lithothamniae* fragments [53–55]. In the Vanoise massif [56], the upper Marbres Chloriteux (Late Paleocene–Early Eocene) disconformably overlies the Maastrichtian Calcschistes à blocs, the Senonian–Paleocene Marbres Chloriteux, and the Jurassic marbles through breccias and/or phosphatic crusts. The latter crusts frequently include Senonian *Globotruncana* in reworked nodules, besides of Late Paleocene–Middle Lutetian *Globorotalia* in the matrix [56,57]. The Schistes de Pralognan (Flysch Noir) disconformably overlie the Early Eocene or Late Cretaceous Marbres Chloriteux and, locally, the Upper Jurassic marbles, with reworked *Lithothamniae* fragments in the lowest Lutetian levels. Likewise in the “3ème écaille” of the classical Briançonnais, the pelagic “Calcschistes en plaquettes” are divided into a Senonian–Lower Paleocene part and an Early Eocene part by a phosphatic level with perfored pebbles and glauconite grains [58]. In the basal level of the disconformable Flysch Noir, the occurrence of early Bartonian pelagic fossils in the argillaceous matrix [59] demonstrates that the late Lutetian–Bartonian benthic foraminifers from the calcarenites are resedimented from some neighbouring shallow marine platform.

Moreover, Late Cretaceous to Eocene disconformities and resedimentation processes seem controlled by normal faulting and block tilting. Fault scarp breccias are frequent in the Senonian–Early Eocene sediments of the Briançonnais domain, at least from the Médianes to the Cottian Alps [52,54,56,57,60–63] and to the external Ligurian Briançonnais [7]. Most of these breccias are dated as Late Cretaceous–Paleocene, and some of them correspond to the reactivation of Liassic normal faults [30,64]. In the Ubaye valley, Gidon et al. [26] describe E-, NE- and NW-trending paleofaults sealed by Late Cretaceous–Paleocene calcschists or even by Eocene Flysch Noir deposits.

5.2. *Source areas for the nummulitic deposits*

The question after the source areas for the Lutetian–Priabonian turbiditic sediments (carrying reworked *Lithothamniae* and benthic foraminifers together with crystalline clasts) now arises. In the Ligurian Alps, the Castelvecchio-Cerisola unit (Ultrabriançonnais = Acceglio zone) was certainly emerged prior to the sedimentation of the Lutetian calcarenites and the Priabonian flysch, as the calcarenites disconformably overlie the varied Mesozoic layers and the

Permian siliciclastic conglomerates [6]. In the Vanoise massif, the Schistes de Pralognan occasionally overlies the Jurassic and Triassic carbonates in the form of a coarse, basal conglomerate with Triassic dolomite and quartzite pebbles [56,57]. Hence, we propose that parts of the internal Briançonnais domain have been uplifted enough such as to reach emersion during the (Early?)-Middle Eocene. Erosion could have easily reached the Triassic quartzites and the Paleozoic basement, as the Triassic carbonates have been almost totally eroded during the Liassic–Middle Jurassic emersion in these areas (Acceglio zone).

Another, and larger potential source area can be recognised in the southernmost Briançonnais domain, i.e. in the autochthonous–parautochthonous Corsica, where Paleocene to Middle Eocene shallow water conglomerates and nummulitic limestones unconformably overlie the Paleozoic basement and its thin Jurassic and/or Late Cretaceous cover [23,65,66]. In the Balagne autochthon [65,67], the crystalline basement is overlain by massive conglomerates interbedded with, and followed upward by nummulitic limestones, which are dated from the Middle–Late Lutetian, and by an Upper Eocene flysch ending with a chaotic wildflysch. In the Corte autochthon, the Zurmulu conglomerates are dated as Late Paleocene–Early Eocene by a nummulitic limestone intercalation [23]. They overlie the crystalline basement and a thin, Ultrabriançonnais-type Mesozoic series (Razzo Bianco sequence) through a contact which was interpreted [23] as a post-metamorphic unconformity. In contrast, we might consider this contact as a ductilely sheared disconformity as it is crosscut by the regional, oblique foliation (pers. obs., A.M. 2000, unpublished). This is supported by the fact that in the neighbouring parautochthonous units, the Eocene flysch, dated by reworked Bartonian nummulites, is affected by the regional, high-pressure, low-temperature metamorphism [68]. The hypothesis of a Corsican source is supported by the overall distribution of the nummulitic limestones in the Briançonnais domain, as the abundance and thickness of these formations decrease north of the Maritime Alps. The northernmost, relatively thick Middle Eocene calcarenite–conglomerate formation occurs in the south Cottian Alps (Cima Piconiera) [69]. Note that the Corsican–Iberian basement was already the source area for the Middle Triassic–Middle Jurassic aluminous argillites and bauxite deposits of the Briançonnais domain [70].

Vanossi et al. [7] suggested that the External domain (which was emerged during the Paleocene–Early Eocene, then partly changed into a shallow marine platform during the Lutetian-early Priabonian [51,71]) could account for the clastic and shallow water biogenic input in the Briançonnais Eocene basin. This hypothesis is unlikely as soon as the Valais-Pyrenean oceanic basin in between the Briançonnais platform and the External domain (Fig. 1B) was not sutured before the Late Eocene [21,22,32]. As suggested by Ceriani et al. [36], the External, Subbriançonnais and Briançonnais basins likely merged into a single trench basin during the Priabonian, but internal sources from the orogenic prism dominated in its internal parts (cf. basaltic clasts and Helminthoid Flysch olistoliths in the Upper Flysch Noir of the Marguareis massif).

5.3. Geodynamic interpretation

The Late Cretaceous–Eocene tectonic/stratigraphic evolution of the Briançonnais domain can be interpreted in relation with the Europe–Adria convergence during this critical period. In the following, we use the geochronologic time scale compiled by Gradstein and Ogg [72]. During the Late Cretaceous–Eocene (98.9–33.7 Ma), the Briançonnais domain was part of the lower plate of the Alpine (Piemont–Ligurian) subduction zone, should this continental plateau be the distal part of the European margin, or the northern tip of the Iberian plate (see Section 2). The subducting plate displayed, on the external (NW) side of the trench, a flexural bending zone characterised by extensional faulting, and presumably by a foreland bulge (Fig. 9A), as observed in many active subduction zones [16,17]. While the leading edge of the subducting plate, i.e. the Piemont–Ligurian oceanic domain was being consumed in the subduction zone (which occurred from the Late Cretaceous onward [21,30,33–35]), the Briançonnais domain had to cross the bulge (Fig. 9A, B) before being buried beneath the orogenic wedge (Fig. 9C). We consider that the role of the frontal bulge might be recognised in the whole Briançonnais domain, at least in the south western Alps, through conspicuous effects, i.e. (i) extensional faulting, responsible for thickness variations of the Senonian–Early Eocene sedimentation, fault scarp breccias, and for a Middle–Late Eocene unconformity, related to superimposed disconformities; (ii) a Late Cretaceous–Early Eocene crustal uplift, responsible for the increased sedimentation rate (Senonian-Paleocene calcareous muds following upward the starved sedimentation of the hard ground episode [28–30]), then for the partial emersion of the internal Briançonnais; and (iii) a Middle–Late Eocene subsidence, just predating the Briançonnais subduction.

In the sketch model (Fig. 9), the geometry of the bulge (total width: 300 km; distance of the outer high to the trench axis: 100 km) is chosen as an approximation of the values observed in active settings [16,17]. The 60 km width of the Briançonnais plateau is a compromise between that of the palinspastic restorations by Lemoine et al. [28], Tricart et al. [29] and Michard and Henry [62], which range from 100 to 30 km. The model assumes a Briançonnais–Adria convergence rate of 1 cm/year, which is a reasonable estimate in the frame of the Tethyan plate tectonics [21]. As discussed by Cliff et al. [73], such a convergence rate might fit the most reliable isotopic datings of the Sesia schists and Piemont–Ligurian eclogites, respectively 70–65 Ma and 60–40 Ma, or 46–43 Ma, according to the more recent synthesis by Dal Piaz et al. [74]. In accordance with such a low convergence rate, the subduction dip should have been

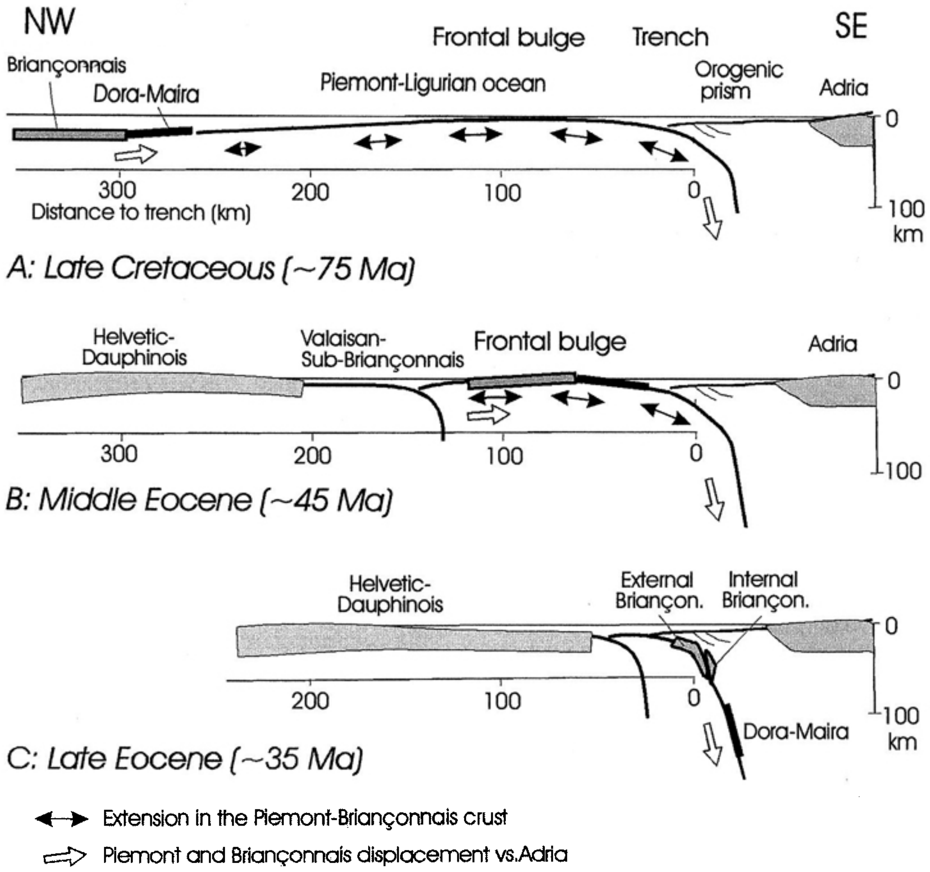

Fig. 9. Sketch model of the displacement of the Briançonnais plateau towards, and eventually within, the subduction zone, which consumed the Piemont–Ligurian ocean (main Alpine subduction zone). Adria-Briançonnais convergence rate: 1 cm/year. Stages A and B show the crossing of the frontal bulge by the Briançonnais plateau. Stage C corresponds to the burial of the Briançonnais beneath the Upper Penninic orogenic prism; the internal Briançonnais units detached from the subducting plate and underwent exhumation processes some time before the Dora-Maira units. The Valais subduction is shown in stages A and B after [21]. Vertical scale approximative; the varied domains are represented by their crust, their sedimentary cover is not differentiated.

steep (about 60°), as assumed by Stampfli et al. [21] for the Late Cretaceous stages. Note that the Europe–Adria convergence rate increased up to about 2 cm/year during the Paleocene–Eocene due to the closure of the Valais ocean [21,33].

The most recent stages of the Briançonnais displacement relative to the bulge-trench-subduction zone system are the best constrained, at least in the French–Italian Alps. In particular, the moment when the external Briançonnais reached the trench (Fig. 9C) is recorded by the emplacement of the olistostromes with exotic blocks from the accretionary prism, at about 35 Ma (Middle–Late Priabonian). The earlier locations of the Briançonnais plateau relative to the bulge are deduced from the Late Eocene location, assuming a constant convergence rate. The internal and external Briançonnais areas would have been coincident with the outer high (top of frontal bulge) at about 51 Ma and 45 Ma (Fig. 9B), respectively, consistent with the age of the maximum uplift recorded by the Early–Middle Eocene erosional event of the internal Briançonnais. The uplift amplitude, 800–1000 m in the flexural model presented by Stampfli et al. [21], might account for the emersion of the internal shoulder of the Briançonnais plateau, as shown in Vanoise and Ligurian Alps. The Briançonnais plateau would have been entering the flexural bulge domain around 71 Ma ago (Fig. 9A), which is compatible with the extensional faulting and bathymetric decrease recorded during the Senonian–Paleocene.

5.4. Discussion

The above model (Fig. 9) suggests some dates for the Penninic metamorphic events, which can be compared with the available, recent isotopic datings. Our model is constructed in the frame of the paleogeographic–geodynamic setting (Figs. 1B and 9A), which is usually assumed to predict metamorphic ages increasing from the Briançonnais to the Dora-Maira–Monte Rosa massifs, to the Piemont–Ligurian meta-ophiolites. In fact, recent datings of the eclogitic meta-ophiolites range between 50–42 Ma [74–76], consistent with our reconstruction (Fig. 9A, B). As to the Dora-Maira–Monte Rosa massifs, the available ages from high-retentivity minerals from the eclogitic, HP-UHP assemblages range from 38–40 Ma [77] to 35 ± 1 Ma [75,78] or 33 ± 1 Ma [79]. This is roughly consistent with our sketch model (Fig. 9C), provided the corresponding thin crustal units were not detached from the subducting lithosphere. In contrast, isotopic datings of the Briançonnais peak metamorphism in the internal Grand Saint Bernard nappe, ~38 Ma Rb–Sr white micas ages in the Entrelor-Nomenon backthrust [80], and 41–36 Ma Ar–Ar white micas ages in the Siviez–Mischabel nappe [81], seem contradictory to our model. This can be explained assuming that these units (by contrast with the Dora-Maira ones) were detached from the subducting plate, some time before the Late Eocene 35 Ma stage (Fig. 9C). Indeed, if not detached from the subducting plate, the internal Briançonnais would have reached at that time ~60 km depth. This depth exceeds by ~30–40 km that recorded by the aragonite- and Mg-carpholite-chloritoid-bearing rocks from the internal Briançonnais of western Vanoise ([82,83] and Goffé, person. com., 2002), and by about 20 km the maximum burial depth of the most internal Acceglio units, equilibrated in the garnet-bearing blueschist/eclogite facies assemblages [84,85]. Therefore, we have to assume that the internal Briançonnais units had been previously detached from the subducting plate, as proposed by several authors [33,34]. In our model, these units reached their maximum burial depth (20–40 km) at ~39–37 Ma, consistent with the reported isotopic datings, then detached from the subducting lithosphere. Similarly, the external Briançonnais units reached their maximal burial depth (~10–20 km) at about 34–33 Ma (assuming a constant subduction rate), then detached.

On the other hand, our model predicts normal faults longitudinal or moderately oblique [86] relative to the trench orientation, i.e. trending close to NE before the Alpine collision (according to the current reconstruction of the pre-orogenic Alpine domain, e.g. [21,30,33]). Recent paleomagnetic studies in the Marguareis massif [87] suggest post-Eocene, anticlockwise rotations of ca. 117° about vertical axis relative to stable Europe. Applying a clockwise rotation of the same value to the N-trending paleofaults (MF and CPF) of the Marguareis massif, we restore their initial, pre-orogenic orientation at ca. N63E, consistent with the prediction of our model.

Our reconstruction of the Briançonnais evolution in the French–Italian Alps is broadly in line with Stampfli et al. [21] model for the Swiss Alps, at least as far as the Late Cretaceous interval is concerned. These authors propose that the bulge could have been responsible for the hiatuses and breccias in the Late Cretaceous sedimentation of the Briançonnais domain, and possibly for the late Maastrichtian–Paleocene intraplate volcanism described by Deville [88]. As a cautionary remark, Stampfli et al. [21] emphasise that the Valais subduction could have uplifted the Briançonnais plateau in a similar fashion as the bulge related to the Piemont–Ligurian subduction (see also Ceriani et al. [36]). This must be considered for the Middle–Late Eocene span of time too, which corresponds to the end of the Valais subduction [21,32,36,89]. However, the Valais crust was about 100 Myr old at that time, and hence had low buoyancy then. This makes the hypothesis of the Briançonnais being uplifted by the Valais crust unlikely. Nevertheless, we emphasise that our model must be taken as a working hypothesis which has to be improved by taking into account not only the possible effects of the Valais subduction, but also those of the northward translation of the Briançonnais terrane during the Eocene, as postulated by Stampfli et al. [21,22].

6. Conclusion

We presented a new stratigraphic and structural dataset collected in the Marguareis massif of the Maritime–Ligurian Briançonnais. Based on this local dataset, and on a review of the published, stratigraphic and structural data from the Briançonnais zone of the French–Italian Alps and Corsica, we inferred a new geodynamic interpretation of the evolution of the Briançonnais domain during the Late Cretaceous–Middle Eocene. This interpretation calls upon the occurrence of a frontal bulge in the lower plate of the Piemont–Ligurian subduction, crossed by the Briançonnais plateau during the Late Cretaceous–Middle Eocene.

The scenario presented here above for the French–Italian Alps and Corsica points toward an ongoing process of subduction of the Briançonnais domain during the Middle-Late Eocene, certainly not before 45 Ma. In the Swiss Alps, a similar conclusion is supported by Stampfli et al. [21,22], whereas Schmid et al. [33] and Schmid and Kissling [90] assume that the Briançonnais units (Tambo, Suretta, Schams) were subducted during the Paleocene–Early Eocene. The discussion of the possibility that the Briançonnais subduction could have been diachronic from the north to the south of the western Alps would be beyond the scope of the present paper.

Acknowledgements

C. Chopin and B. Goffé provided useful comments on an early draft of the manuscript. A.M. is endebted to B. Goffé and M.-D. Loÿe for logistic support at Ecole Normale Supérieure, and to J. Ferrandini and P. Vellutini for helpful guidance in the field and support in Corsica. We thank M. Collombet for the communication of a preprint of her paper. Reviews by Stephan Schmid and Gérard Stampfli are gratefully acknowledged. This paper is dedicated to the memory of Rafaella Ruffini, from Torino laboratory, deceased September 2002.

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