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Structures and tectonic evolution of the external zone of Alpine Corsica

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Abstract—This paper presents a structural analysis of the external zone of Alpine Corsica, including the autochthonous domain and overlying external nappes (Santa Lucia and Balagne nappes). Two stages of nappe emplacement are identified occurring prior to and after the deposition of the Eocene sediments which were laid down upon first generation thrust contacts but are imbricated with their composite (continental and ophiolitic) basement by second generation thrusts. Five generations of structures with regional extent have been distinguished. However, the first generation has not been recognized within the visible part of the autochthon domain.

Eoalpine first generation structures, restricted to allochthonous units, and Late Eocene to Early Oligocene second generation structures were nearly contemporaneous with the two stages of thrusting. The precise significance of E–W third generation structures is poorly understood. Broadly N–S fourth generation structures resulted from Oligocene compressive tectonics (folding and local backthrusting). Finally, fifth generation structures were generated during a Miocene extensional stage.

These results are partly consistent with structural features previously reported in the southern and the northern outcrops of the Schistes lustrés, i.e. the main part of the allochthonous domain. A summary of a regional tectonic evolution is thus proposed for Alpine Corsica from Eoalpine obduction to Miocene extension.

INTRODUCTION

DUE TO a long and polyphase tectonic evolution, Alpine Corsica is structurally complex. In previous studies, many authors have described successive tectonic structures and associated metamorphic parageneses which they have related to major geodynamic phases (Mattauer & Proust 1976, Caron 1977, Caron & Bonin 1980, Mattauer *et al.* 1981, Principi & Treves 1984, Harris 1985a,b, Warburton 1986, Waters 1989, 1990). Despite the differences between the models proposed, the authors mainly agree to distinguish an Eoalpine (Mid to Late Cretaceous) ophiolite emplacement (obduction) upon the European margin partly in high pressure–low temperature conditions (well preserved blueschists) and an Alpine *s.s.* (Eocene to Oligocene) tectonic stage related to collision, mainly in conditions of greenschist overprint (isostatic recovery). This sequence has chiefly been established from studies in internal Alpine nappes. New and consistent results are given in this paper from the external zone of Alpine Corsica, i.e. the autochthonous domain (except the Tenda Massif) and the Balagne and Santa Lucia nappes (Fig. 1). The purpose of this paper is to determine the relationships between the Alpine nappes and their basement and to elucidate further the Alpine evolution in Corsica from Late Cretaceous to Miocene times. The results are partly determined from the tectonic analysis of Eocene sediments which are of particular importance for two reasons. Firstly because they are exposed, in autochthonous and allochthonous positions, along the contact zone between Alpine nappes and their basement (Fig. 1) and their outcrops occur within different structural settings which help constrain the model of progressive thrust tectonics. Secondly, they represent a valuable chronological marker since they were deposited after the Eoalpine tectonics but during or prior to the Alpine *s.s.* events.

After a description of the Alpine units, we shall examine the structural settings of Eocene sediments and consequently differentiate major thrusting events. This is followed by a detailed structural analysis within studied terrains and a comparison of the results with those previously reported in Alpine Corsica.

GEOLOGICAL FRAMEWORK: ALPINE UNITS OF CORSICA

Alpine Corsica, located in the northeastern part of the island mainly consists of various nappes which were deformed, metamorphosed and emplaced during the Alpine orogeny. The foreland of these nappes and their substratum consist mainly of Variscan basement which covers about two thirds of Corsica in its western and southern part and is chiefly made of Carboniferous and Permian magmatic rocks (Caron & Bonin 1980, Rossi *et al.* 1980, Menot 1990). Few and small, highly metamorphic terrains occur in western and southern Corsica. Previously attributed to the Precambrian (Durand-Delga 1978, 1984, Caron & Bonin 1980, Rossi *et al.* 1980), these units are now assumed to be Variscan (Menot 1990, Lardeaux *et al.* in press). Remnants of Mesozoic to Cenozoic (locally Palaeocene but mainly Lower and Middle Eocene, Table 1) cover of mainly detritic character are located at the eastern margin of the autochthonous domain (Fig. 1). Alpine nappes are locally separated from this autochthon by the following, most likely parautochthonous (Nardi *et al.* 1978,

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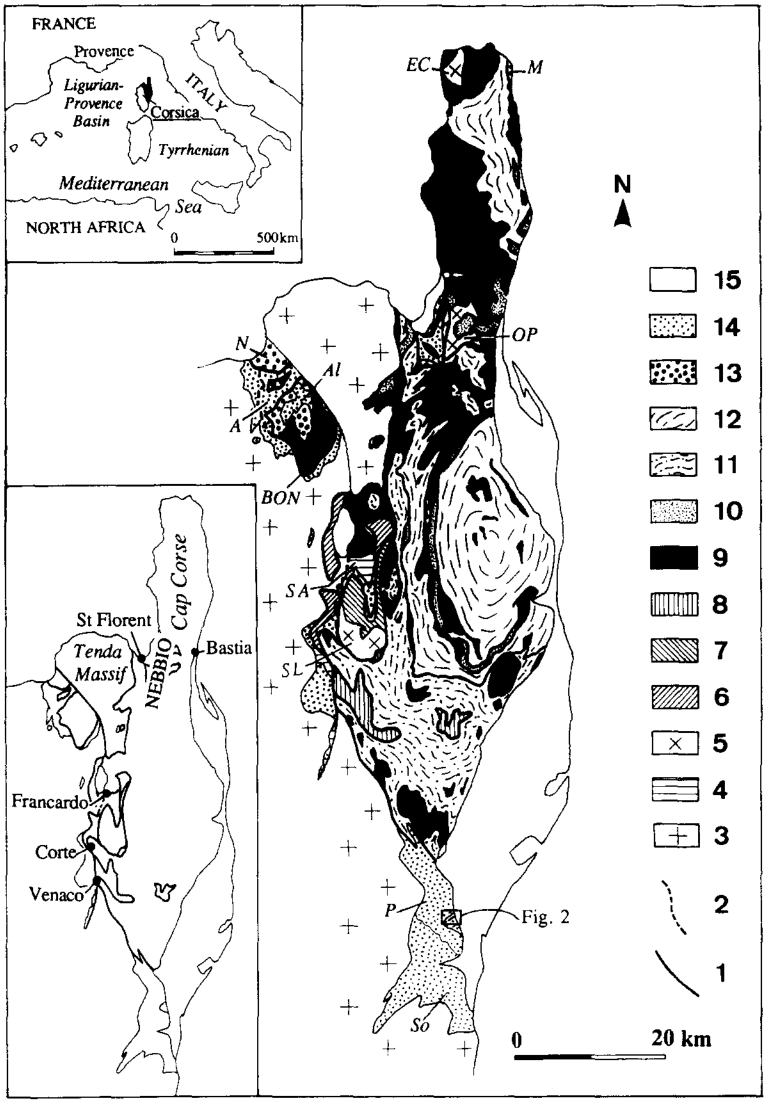
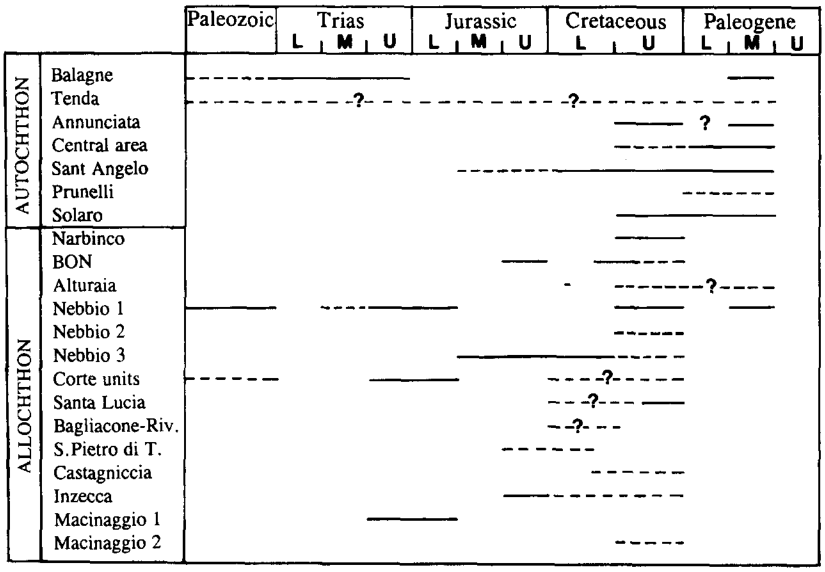


Fig. 1. Location of the geographic names cited in the text and main tectonic units of Alpine Corsica (modified from Caron & Bonin, 1980). 1—Limits of main allochthonous units. 2—Limits of main parautochthonous units. 3—Variscan basement. 4—Autochthonous and parauthochthonous Mesozoic groups. 5—Gneisses and granites of allochthonous domain. 6—Permian and Mesozoic groups of the Corte units. 7—Mesozoic group of the Santa Lucia Nappe. 8—Bagliacone–Riventosa Group (included in the Schistes lustrés). 9—Ophiolites. 10—Santo-Pietro-di-Tenda Group (Schistes lustrés). 11—Inzecca Group. 12—Castagniccia Group. 13—Mesozoic sediments present in high-level nappes ('Nappes supérieures'). 14—Eocene (autochthonous to allochthonous) deposits. 15—Neogene and Quaternary deposits. A = Annunciata Formation. Al = Alturaia Formation. BON = Balagne ophiolitic Nappe. EC = Ersa–Centuri klippe. M = Maccinaggio units. N = Narbinco Nappe. OP = Oletta–Pigno granites. P = Prunelli Group. SA = Sant-Angelo unit. SL = Santa Lucia Nappe. SO = Solaro Group.

Amaudric du Chaffaut 1982, Jourdan 1988), units : the Annunciata unit (Balagne) which consists solely of the Eocene Annunciata Formation and the Sant Angelo unit (east of Corte) which consists of a succession of Mesozoic to Cenozoic formations (Fig. 1 and Table 1).

The nappes comprise abundant ophiolitic fragments, granitic or gneissic bodies and large masses of sediments which were initially deposited upon oceanic or continental basement (Fig. 1). The ophiolites were derived from a Piemont–Ligurian oceanic basin (or Ligurian Tethys). This basin, which separated European and African plates, developed mainly during Jurassic times (trondjhemites associated with ophiolites in Corsica have been dated at 161 ± 3 Ma, Ohnenstetter *et al.* 1981) in relation to the opening of the Atlantic ocean (see global syntheses of Dercourt *et al.* 1986, Ziegler 1987, Gealey 1988, Coward & Dietrich 1989, Alvarez 1991). The commonly accepted tectonic model for the emplacement of Corsican ophiolites during the Alpine orogeny is of intra-oceanic subduction being blocked by the arrival of European continental basement (including the Variscan domain of Corsica) into the subduction zone, initiating the westward obduction of previously subducted oceanic crust over continental basement (Mattauer & Proust 1976, Mattauer *et al.* 1981, Gibbons *et al.* 1986). Principi & Treves (1984) propose an alternative model. They consider that Alpine Corsica constituted a part of a Corsica–Apennines double-vergence accretionary prism related to subduction of the Piemont–Ligurian oceanic plate under the European plate, during Late Cretaceous to Late Eocene times. The 'obducted' ophiolitic units would have been scraped off the subducting plate and emplaced onto the European margin by an 'upward flow'.

Table 1. Dated or assumed age of Upper Paleozoic (Upper Carboniferous or Permian) to Palaeogene rock units of Alpine Corsica (BON = Balagne ophiolitic nappe; L = Lower; M = Middle; U = Upper). Full line: age obtained from fauna or deduced with slight uncertainty from characteristic facies referred to formation dated elsewhere in the Alpine domain. Dashed line: uncertain age admitted or debated by authors, in absence of paleontological data or characteristic facies (? = strong uncertainty). Data compiled from Durand-Delga (1978, 1984), Caron & Delcey (1979), Rieuf (1980), Amaudric du Chaffaut (1982), Jourdan (1988), Lluch (1989) who proposed the distinction of three and two main units within, respectively, the Nebbio and Macinaggio allochthonous terrains and Caron (personal communication)



Classically, most allochthonous units are grouped into the so-called 'Schistes lustrés' which, as in the French and Italian Alps, include both ophiolites and monotonous calcschists which have been highly deformed and metamorphosed at high pressure–low temperature (Caron 1977, Caron *et al.* 1981, Mattauer *et al.* 1981, Guiraud 1982, Harris, 1984, Péquignot 1984, Péquignot *et al.* 1984, Warburton 1986, Lahondère 1988, Waters 1990). Several interpretations have been proposed for the subdivisions and the paleogeographic significance of the Corsican Schistes lustrés (see Durand-Delga 1984, and Gibbons *et al.* 1986, for a summary of classical interpretations and Principi & Treves 1984 for an alternative proposition). Here, we retain the interpretation of Caron & Delcey (1979), Caron *et al.* (1979) and Rossi *et al.* (1980) who distinguished four main stratigraphic groups (Fig. 1, Table 1) : 1—the Bagliacone–Riventosa Group previously attributed to the Trias (Caron 1977, Caron & Delcey 1979) but most likely Lower Cretaceous in age (Durand-Delga 1984, Caron personal communication) and which is considered to have been deposited onto the European continental margin; 2—the Santo-Pietro-di-Tenda Group (Upper Jurassic–Lower Cretaceous?) which was probably deposited onto oceanic floor but close to the European margin since the group includes continental debris (Caron & Delcey 1979, Caron & Bonin 1980) though Durand-Delga (1984), Warburton (1986) and Waters (personal communication) consider this group was directly deposited onto the continental basement; 3—the Castagniccia Group (Upper Cretaceous?) which was probably deposited upon the Santo-Pietro-di-Tenda Group; and 4—the Inzecca Group (Upper Jurassic to Lower Cretaceous?) which is clearly associated with ophiolites and deposited far from continental influence in the Ligurian palaeogeographic domain. These groups also constitute major tectonic units.

Alpine nappes are also represented by continental units in external positions (generally attributed to the European margin) such as the Santa Lucia Nappe and the Corte units (Fig. 1). The Santa Lucia Nappe consists of Variscan basement overlain by Lower Cretaceous? conglomerates and Lower Senonian flysch (Rieuf 1980), whereas the Corte units include characteristic formations of Triassic and Liassic age (Rieuf 1980, Amaudric du Chaffaut 1982) (Table 1). The metamorphism undergone by these units is generally low grade (prehnite–pumpellyite) with however very scarce indicators of high-pressure conditions; blue amphibole in Corte units, glaucophane or lawsonite in the basal part of the Santa Lucia Nappe (Amaudric du Chaffaut & Saliot 1979). According to recent interpretations, the Santa Lucia Nappe and the Bagliacone–Riventosa Group (Schistes lustrés) could belong to the same unit (Durand-Delga 1984, J. M. Caron personal communication).

Other ophiolitic or continental units (Balagne, Nebbio and Macinaggio nappes and other small units) constitute high level nappes (or 'Nappes supérieures') affected by very low- to low-grade metamorphism (Durand-Delga 1978, 1984, Amaudric du Chaffaut & Saliot 1979). Superficial ophiolitic units (e.g. in Balagne or in Nebbio, Fig. 1) are generally considered to be of more internal origin than the ophiolitic Schistes lustrés nappes (Mattauer & Proust 1976, Mattauer *et al.* 1981, Jourdan 1988, Egal 1989) although according to Durand-Delga (1984) and Lluch (1988), these units originate in a more external position than the 'Schistes lustrés' units. Other superficial nappes as the Narbinco and the Macinaggio nappes (Fig. 1), have uncertain origin.

A number of granitic or gneissic bodies are incorporated in the allochthonous domain. Some of them, including the Oletta-Pigno unit (west-northwest of Bastia, Fig. 1) have a clear affinity with the European basement (Durand-Delga 1984, Warburton 1986). The Ersa-Centuri klippe (Fig. 1), according to different authors, originates from the European crust (Warburton 1986, Waters 1989) or from the Apulian crust (Harris 1984, Gibbons *et al.* 1986, Lardeaux *et al.* 1992) or also from a small continental block within the oceanic domain (Principi & Treves 1984).

Deposits of Lower to Middle Miocene age rest unconformably upon, and are unaffected by, the Alpine thrusts (Fig. 1).

STRUCTURAL SETTINGS OF EOCENE DEPOSITS: TWO STAGES OF ALPINE NAPPES EMPLACEMENT

A series of E–W structural sections across the external zone of Alpine Corsica display the complex relationships of Eocene sediments with autochthonous continental basement and the Alpine nappes.

In the southeastern area of Corsica, Eocene sediments rest unconformably upon the continental basement (which however have locally been emplaced by late backthrusts onto Eocene sediments), or are in contact with metasedimentary terrains (Figs. 1 and 2) whose origin and present relations with Eocene deposits are controversial (Amaudric du Chaffaut 1982, Durand-Delga 1984, Counas 1986). New observations indicate, in agreement with Amaudric du Chaffaut (1982), that the metasedimentary terrains clearly belong (at least partly) to the Ligurian supra-ophiolitic Inzecca Group as characteristic facies have been recognized (Egal 1989). According to Amaudric du Chaffaut (1982), these allochthonous terrains were tectonically emplaced before the deposition of Eocene sediments, and therefore the contact between the allochthonous metasediments (Inzecca Group) and the Eocene deposits is stratigraphic in nature though deformed by subsequent tectonic phases. Durand-Delga (1984) and Counas (1986), however, considered that the allochthonous metasediments have been overthrusted onto Eocene deposits. According to new detailed mapping and evidence from way-up criteria, the Eocene sediments overlie the allochthonous metasedimentary formations and exhibit a normal stratigraphic position (Fig. 2). Moreover, there is no structural argument to suggest that Eocene was thrusted onto the allochthonous formations. So, following Amaudric du Chaffaut (1982), new observations lead to the conclusion that in southeastern Corsica, the Eocene sediments were deposited partly onto the autochthonous basement and partly onto Ligurian metasediments after these had previously been thrust onto the European autochthonous margin (cross-section A in Figs. 3 and 4). Thus, Eocene sediments rest on the early tectonic contact between these units.

About 10 km to the north (sector B, Fig. 3), the relationships between Eocene sediments and adjacent units are more complicated. Eocene Prunelli flysch (the main formation of the Prunelli Group, Fig. 1) is involved in a tectonic imbrication dipping to the ENE and comprising from bottom (west) to top (east) (cross-section B, Fig. 4): autochthonous granite, Eocene flysch, gneissec Variscan unit, Schistes lustrés (Bagliacone–Riventosa Group overlain by Inzecca Group), Eocene flysch and serpentinites. In comparison with sector A (Fig. 3), the contacts between Eocene terrains and underlying granites or Schistes lustrés, are thought to be stratigraphic. On the other hand, the superposition of the Schistes lustrés and serpentinites onto the Eocene sediments is tectonic. Restoration of the section produces the same initial configuration as in sector A (Fig. 3). Thus, the present lithological pile of this sector results partly from a tectonic imbrication which postdates the deposition of Eocene sediments upon both granitic basement and allochthonous units (cross-section B, Fig. 3). The tectonic superposition of oceanic Inzecca Group onto the continental Bagliacone–Riventosa unit is considered, from observations southeast of Corte (Caron 1977), to result from the Eoalpine emplacement of the ophiolitic nappes.

Further to the north (sectors C and D, Fig. 3), the Eocene and Palaeocene formations are essentially autochthonous or parautochthonous and largely overlain by Alpine nappes. Their present geometrics are thus greatly influenced by thrusting after the deposition of the Eocene sediments. In the Balagne area (sector D,

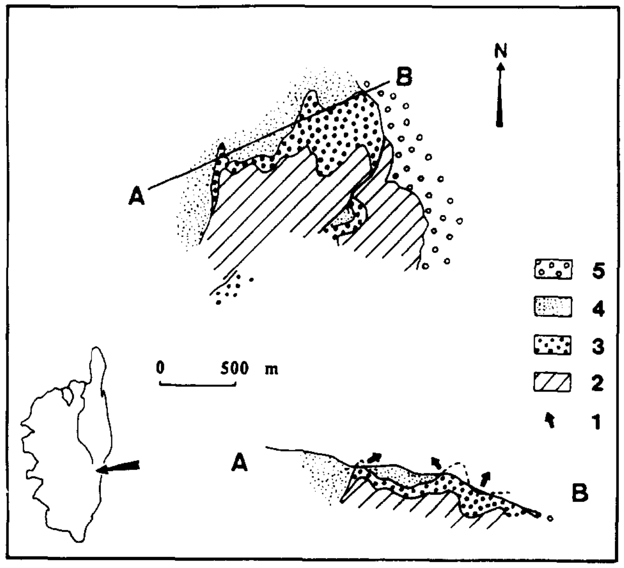


Fig. 2. Map and cross-section (A–B) of autochthonous Eocene sediments and underlying allochthonous metasediments, southeastern Corsica (location on Fig. 1). 1—Way-up of bedding (recorded from Prunelli flysch). 2—Allochthonous metasediments (Inzecca Group). 3—Eocene conglomerate (Prunelli Group). 4—Eocene Prunelli flysch (Prunelli Group). 5—Neogene sediments.

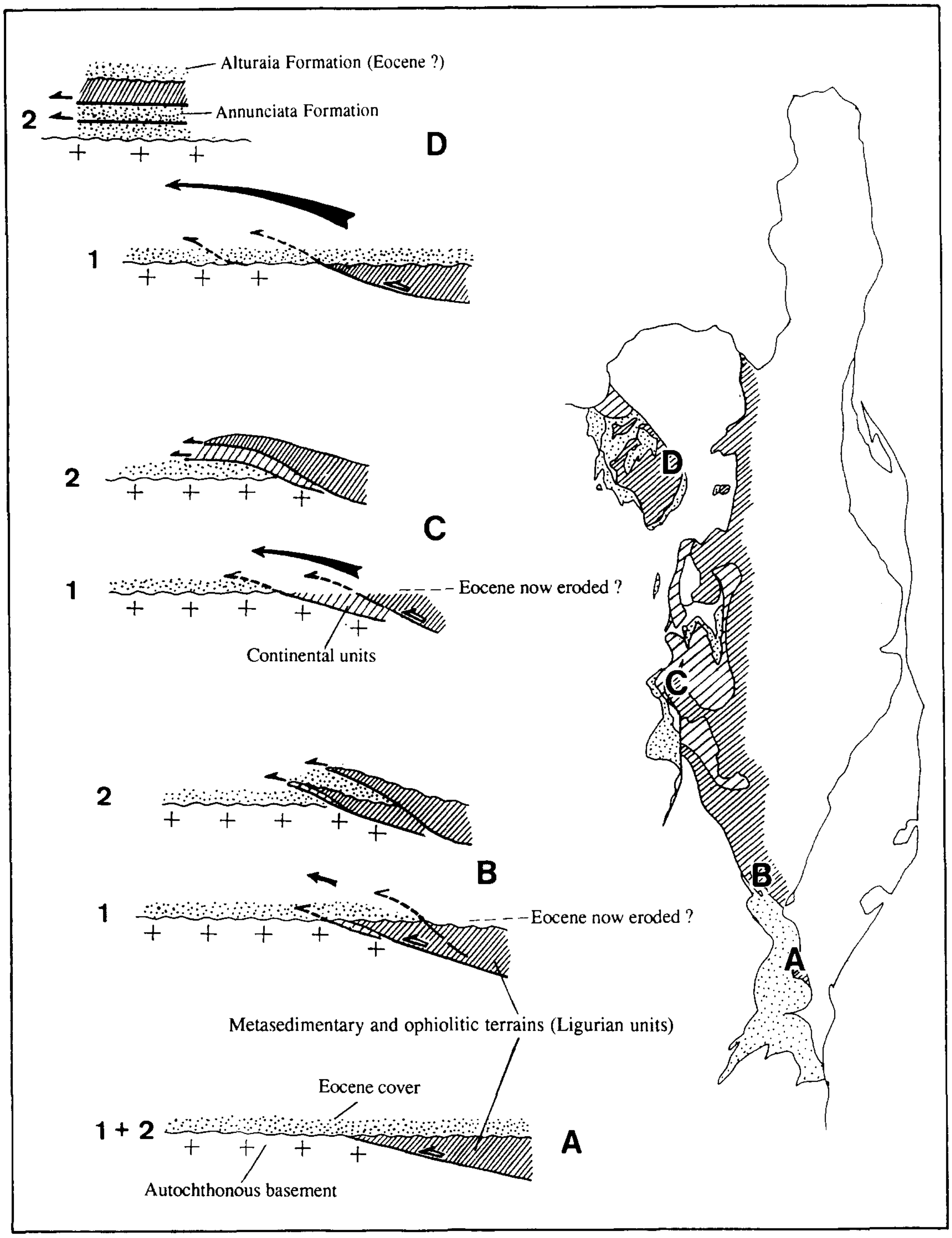


Fig. 3. Sketch of the structural settings of the autochthonous and external allochthonous units before (1) and after (2) the Late to post-Eocene thrusts. The displacement associated with these thrusts, represented by large arrows, increases from the south to the north. The orientation of the sections is not labelled because precise thrusting direction is unknown.

Fig. 3), a thick clastic cover lies unconformably upon a mainly ophiolitic nappes pile which overthrusts the Eocene parautochthonous Annunciata Formation (Bonnal *et al.* 1973, Nardi *et al.* 1978, Jourdan 1988) (Fig 1, and cross-sections of sector D in Fig. 3 and sector E in Fig. 4). The upper clastic cover has mainly been mapped as the Alturaia Formation, undated but possibly of Eocene age (Bosma 1956, Nardi *et al.* 1978, Jourdan 1988) (Table 1). However, in some places and according to different authors, this clastic cover has been mapped either as the Alturaia Formation or as the Annunciata Formation (compare Bonnal 1973 and Nardi *et al.* 1978). This reveals local strong similarities between the latter two formations. Thus, the Alturaia Formation and the Annunciata Formation are assumed to be laterally equivalent. Moreover, these formations are interpreted to represent the eastern continuation of the autochthonous Eocene terrains (cross-section D in Fig. 3). Consequently, by analogy to the southern area (sector A, Fig. 3), it is proposed that the autochthonous Eocene sediments and the Annunciata and Alturaia Formations represent lateral variations of a sedimentary cover initially deposited upon both the ophiolitic nappe and the autochthonous granitic basement, and were subsequently involved in late tectonic duplication (sector D in Fig. 3).

In summary, the structural settings of the Eocene deposits (including Palaeocene) along the contact zone between Alpine and Variscan domains can be interpreted consistently at the regional scale (Fig. 3). By analogy with observations in the southeastern area, we propose that the sedimentary cover of Eocene age in Corsica was initially deposited (in a 'foreland basin') onto Variscan basement and ophiolitic nappes after Eoalpine nappe emplacement. This Eoalpine thrusting (T_1) clearly implied by the present proximity of Ligurian and autochthonous formations in the southern area (sector A, Fig. 3), is marked further to the north (sector B, Fig. 3) by the tectonic superposition of ophiolitic Inzecca Group onto the continental Bagliacone–Riventosa Group. Thus the Ligurian units were emplaced onto the continental European margin before Eocene times.

After Eocene sediment deposition, late thrusting (T_2) created imbrication of the Eocene deposits and its composite basement. This late- to post-Eocene thrusting event is not revealed in SE Corsica (sector A, Fig. 3), but further to the north the regional structure is greatly influenced by these thrusts. The thrusts displacement increases in magnitude toward the north (Fig. 2) and is particularly important in the Balagne area where the ophiolitic Balagne Nappe constitutes a klippe entirely overlying autochthonous Eocene sediments (Figs. 1, 3 and 4). The T_2 thrusting event post-dates the deposition of Eocene sediments and occurred prior to the Miocene since Miocene formations rest unconformably on all the Alpine thrusts.

SUCCESSIVE ALPINE STRUCTURES: GEOMETRY, CHRONOLOGY AND TECTONIC SIGNIFICANCE

Using interference patterns and geometric characteristics, the sequence of generations of structures described below has mainly been established in the autochthonous domain (Tenda Massif excepted) and in the external Balagne and Santa Lucia nappes. The generations of structures distinguished have not only a local significance but a regional extent. The distinction

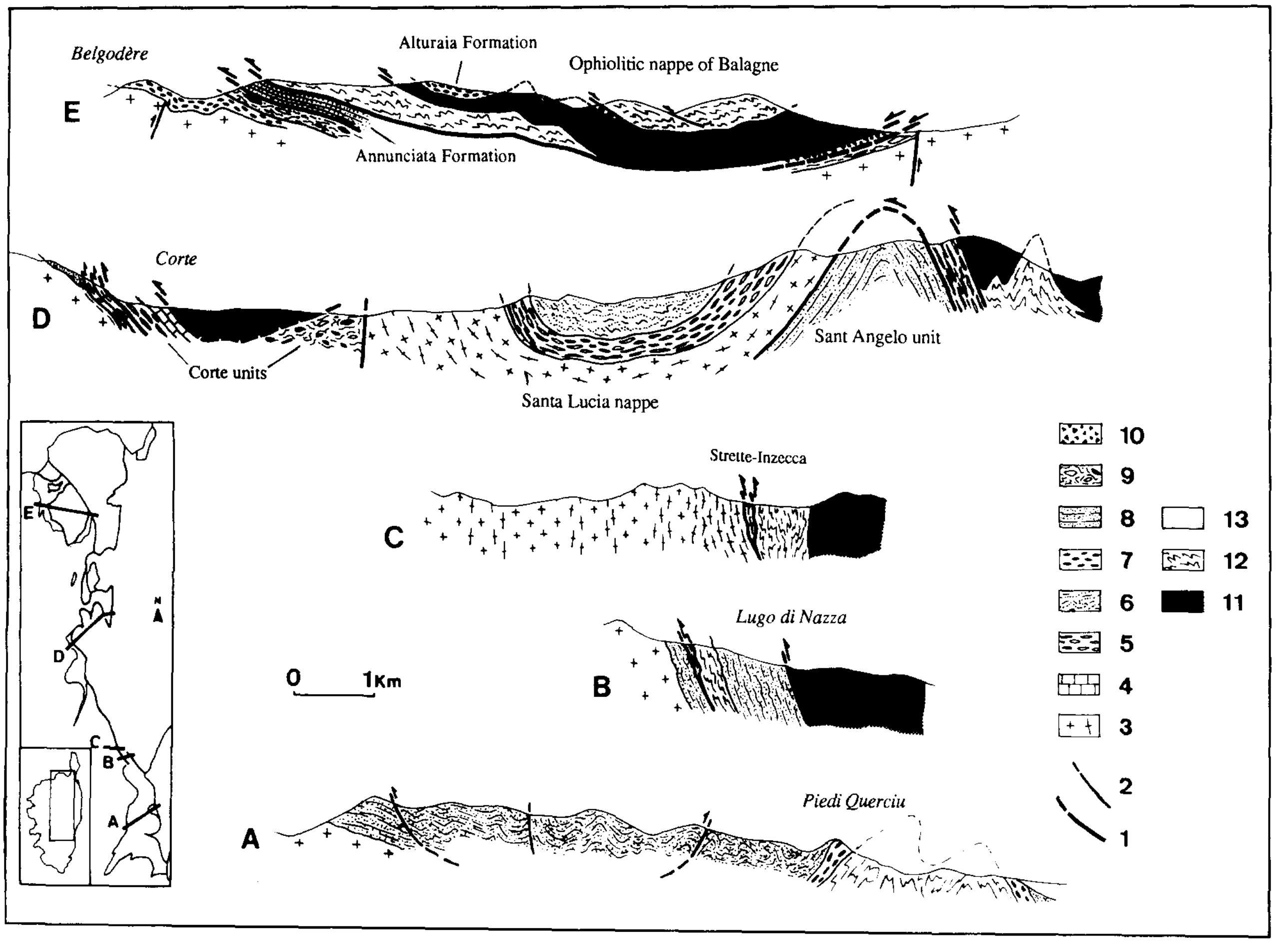


Fig. 4. Broadly W–E cross-sections through the contact zone between Alpine nappes and western autochthon. 1—Thrust planes between major tectonic units. 2—Thrust planes within major tectonic units. 3—Granites or metamorphic Variscan basement (Alpine deformation represented by elongated crosses). 4—Triassic and Liassic formations of the Corte units. 5—Cretaceous (?) conglomerates with calcareous pebbles. 6—Lower Senonian flysch. 7—Eocene conglomerates (and locally nummulites-rich limestones). 8—Flyschs dated or attributed to Eocene. 9—Melanges attributed to Eocene. 10—Ophiolitic breccias. 11—Ophiolites. 12—Schistes lustrés (including the Bagliacone–Riventosa Group). 13—Neogene and Quaternary sediments.

of successive structures does not preclude a progressive history of the deformation.

Within the autochthonous and parautochthonous formations within the studied area, four generations of ductile Alpine structures have been distinguished at the regional scale (Table 2) (Egal 1989, Egal & Caron 1989). All these structures developed after the deposition of the Eocene group : in fact, contrary to previous interpretations (Mattauer & Proust 1975, Amaudric du Chaffaut 1982), it is considered that there is neither a structural nor a metamorphic jump between autochthonous Eocene terrains and underlying Mesozoic formations (Bezert & Caby 1988, 1989, Egal & Caron 1988, 1989, Bezert 1990). Locally observed structural differences are due only to the heterogeneity of the deformation, mainly resulting from lithological (and hence rheological) differences (Egal & Caron 1989), and no Eoalpine ductile tectonics has been recognized within the studied autochthonous area. In the autochthonous Tenda Massif (not studied here), some authors have proposed an Eoalpine age for D_1 tectonics. For example Cohen *et al.* (1981) published a Rb–Sr whole-rock (metamorphosed granodiorite) dating at 105 Ma for the first tectonic event within the Tenda Massif. They consider the Mesozoic Santo Pietro Group, which has suffered Eoalpine HP–LT metamorphism and strong deformation, to represent the sedimentary cover of the crystalline Tenda basement (Mattauer *et al.* 1981, Warburton 1986) though other authors are convinced that the Santo Pietro Group constitutes an allochthonous supra-ophiolitic group thrust upon the Tenda Basement (Caron & Delcey 1979, Durand-Delga 1984). Moreover, it is not clear to what extent the date proposed by Cohen *et al.* (1981), because of the method applied, represents an hybrid age between the genesis of the protolith (granodiorite) and a re-opening of the system during the deformation. In addition, the isochron proposed by Cohen *et al.* (1981) has been drawn from only four analyses including one which occupies a strongly outlying position on the diagram. It is here concluded that the age of the Alpine D_1 tectonics within the autochthonous Tenda Massif is still disputable.

In the Santa Lucia and Balagne nappes, five generations of ductile structures (D_1–D_5) have been distinguished in Cretaceous rocks. In contrast, only four generations have been recognized in the studied autochthon domain. The last three generations in the nappes and in the autochthon have clear geometric similarities and are considered to be contemporaneous (Table 2). Before these three generations, the autochthon and the studied nappes have thus been deformed, respectively, by one and two generations of structures. The first generation of structures within the nappes is considered to be Eoalpine (see below). In contrast, the first structures of the autochthon post-date Eoalpine tectonics (see above) and are here interpreted as being nearly contemporaneous to the second generation of structures of the nappes. Consequently, the first structures recognized within the autochthonous area are assigned to the regional D_2 deformation (Table 2).

The successive structures within the studied autochthonous and allochthonous units are presented below, then they are compared with the structural evolution previously reported in Alpine Corsica. The orientation and the vergence of the structures are referred to the present position of Corsica.

First generation structures

These structures have only been distinguished in allochthonous units (see above) where, in addition, they have rarely been observed mainly because of later tectonic overprints. In the Santa Lucia Nappe, scarce isoclinal F_1 folds deformed by F_2 folds (Fig. 5a) are locally observed. No precise orientation of F_1 folds could be measured. In Balagne, D_1 structures are mainly represented in the Cretaceous cover of the ophiolitic nappe: tight isoclinal F_1 folds deformed by open F_2 folds are frequently observed. They exhibit a mainly N–S axial direction (Fig. 6) with undetermined vergence. They are associated with 'axial-plane' S_1 dissolution cleavage defined by residual opaques and thus formed at shallow crustal level. In the other nappe of Balagne (Narbinco Nappe), there is no direct evidence of D_1 structures (no clear interference pattern) which are however assumed because of frequent inversion of the bedding which occur independently of F_2 folds (Fig. 6).

The vergence of F_1 folds in the Balagne and Santa Lucia nappes is unclear because of important tectonic overprints, but elsewhere in Alpine Corsica, authors

Table 2. Summary of the age, orientation and vergence of successive structures in the autochthon and the Balagne and Santa Lucia nappes

Successive structures and related age	Autochthon	Balagne nappes	Santa Lucia Nappe
S_5, F_5 Miocene	Sub-horizontal S_5 foliation and F_5 axial planes	⟶ *idem.*	⟶ *idem.*
S_4, F_4 Late Oligocene(?)	NW- to NE-trending F_4 folds: upright to gently inclined towards the east	⟶ *idem.*	⟶ *idem.*
S_3, F_3 Oligocene (?)	E–W F_3 folds gently inclined towards the south or north	Not recognized towards the south or north	E–W F_3 folds mainly recumbent
S_2, F_2 Late Eocene (?)	F_2 folds roughly N-trending SW vergence	NW–SW F_2 folds	F_2 folds NE- or NW-trending (F_3 refolding). Vergence?
S_1, F_1 Late cretaceous	Not recognized	Sub-meridian structures (?). Vergence?	Direction?

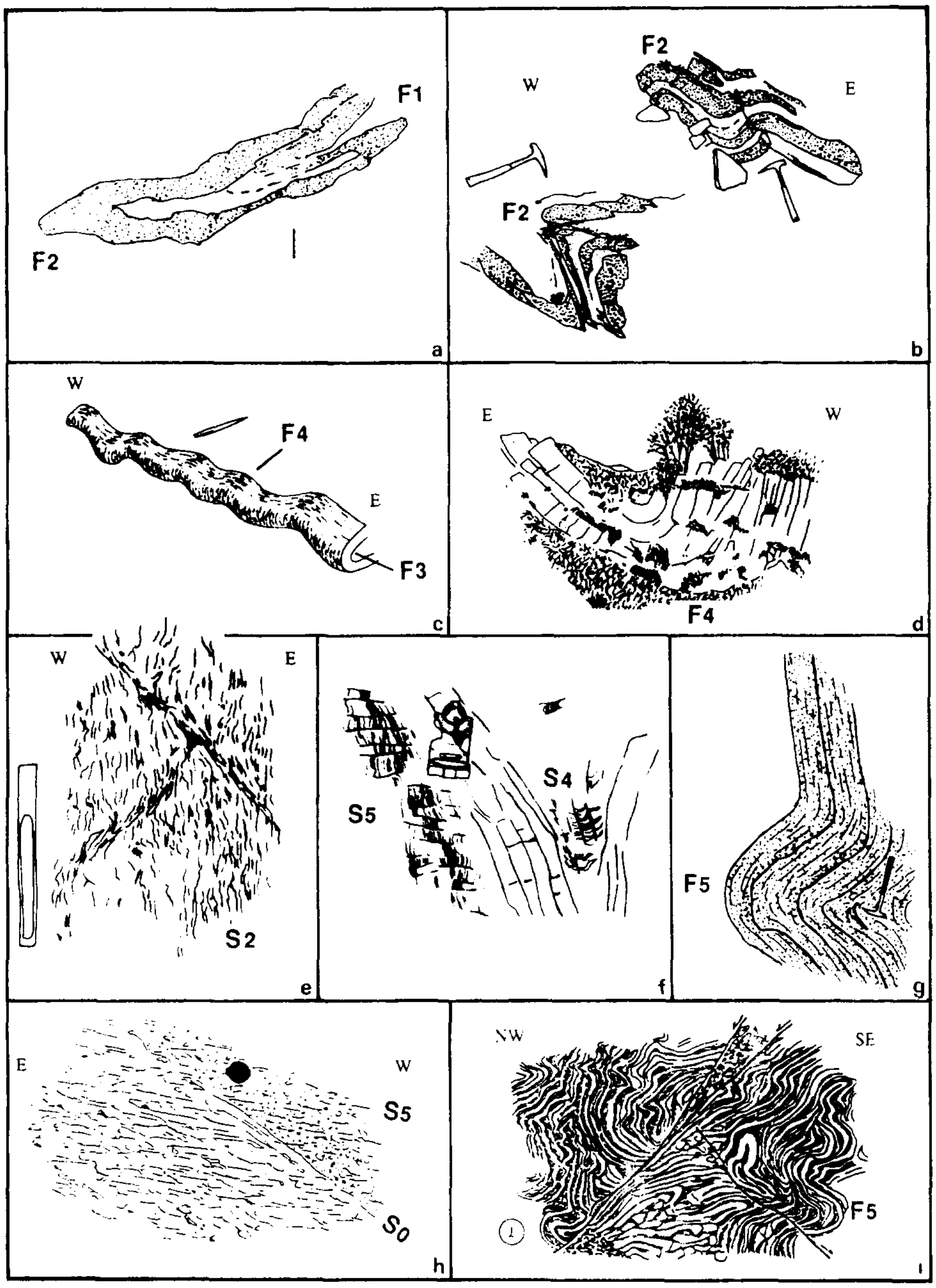


Fig. 5. Field examples of successive structures. (a) F_1 fold deformed by F_2 fold in the Lower Senonian flysch of the Santa Lucia Nappe (scale bar = 5 cm). (b) F_2 folds in autochthonous Eocene sandstones (Monte Cardo, west of Venaco). (c) F_3 fold deformed by F_4 folds in the Lower Senonian flysch of the Santa Lucia Nappe. (d) F_4 fold in autochthonous Eocene flysch near Corte. (e) S_2 schistocity and conjugate reverse decimetric-long shear zones in deformed granites, south-southeast of Venaco. (f) S_4 and S_5 cleavages in the Lower Senonian flysch of the Santa Lucia nappe. (g) F_5 fold in the autochthonous Eocene Prunelli flysch (SE of Corsica). (h) S_5 cleavage in Miocene formation (marls and sandstones near Francardo); scale: black camera lens cap. (i) F_5 folds (deforming F_2 folds) and late normal faults in the allochthonous Bagliacone–Riventosa Group (Tavignano valley, SE Corte); scale: hammer in the circle.

deduce a westwards initial vergence to D_1 structures (Caron 1977, Mattauer *et al.* 1981, Gibbons *et al.* 1986). Thus, the same vergence is here assumed for D_1 structures within the Balagne and Santa Lucia nappes.

The first ductile structures in Alpine Corsica are usually considered to be of Upper Cretaceous (Eoalpine) age, mainly from K–Ar dating (metamorphic blue amphiboles, 'Schistes lustrés') at 90 Ma (Maluski 1977) and also from disputable (see above) Rb–Sr whole-rock dating at 105 Ma in the Tenda Massif (Cohen *et al.* 1981). However, the Lower Senonian (Rieuf 1980) flysch of the Santa Lucia Nappe is deformed by D_1 structures which thus probably appeared in these units during the Upper Senonian, around 60–70 Ma. This age is younger than the one proposed by Maluski (1977), but no serious explanation of this difference can be made because stratigraphic and radiometric age-dating of D_1 structures is still lacking.

These pervasive Eoalpine structures are subject to different interpretations. Mattauer *et al.* (1981) and Harris (1985a,b) from observations in NE Corsica, directly related the first ductile structures to the progressive obduction of 'Schistes lustrés' ophiolitic nappe onto the European margin. Caron (1977) considered the

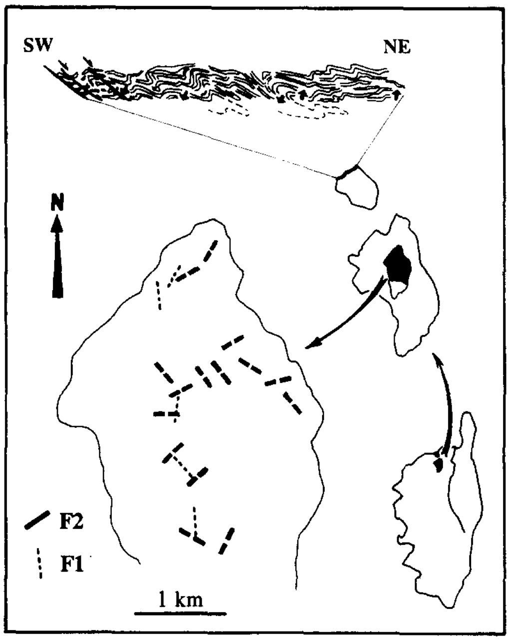


Fig. 6. Cartographic distribution of F_1 and F_2 fold axes in Cretaceous cover of the ophiolitic nappe of Balagne and cross-section across the flysch of the Narbinco Nappe (along the coast) in which F_1 folds are deduced from the way-up of bedding (small black arrows), F_2 folds are abundant, their axes trending around N150.

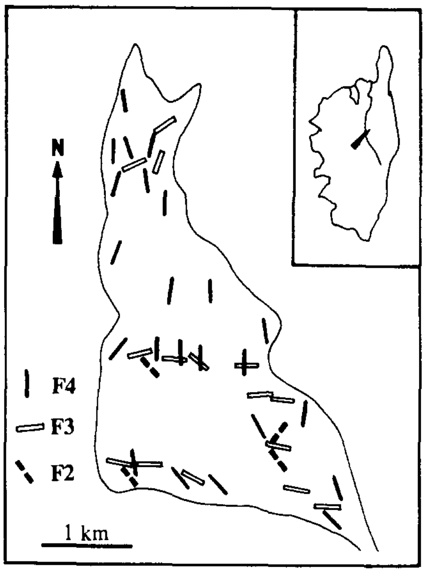


Fig. 7. Cartographic distribution of F_2, F_3 and F_4 fold axes in the Lower Senonian flysch of the Santa Lucia Nappe.

obduction occurred prior to the D_1 pervasive deformation. Finally, according to Warburton (1986), pervasive D_1 structures formed prior to obduction thrusting. In the Balagne and Santa Lucia nappes, no new information was collected to favour one model over the other.

Second generation structures

The Narbinco Nappe of Balagne exhibits numerous centimetric to metric folds with axial direction around N150 and overturned vergence toward the southeast (Fig. 6). These folds deform bedding with variable way-up, suggesting the existence of F_1 folds (Fig. 6), so we interpret the former as F_2 folds. They are associated with S_2 axial plane dissolution cleavage emphasized by residual minerals. Numerous lenticular quartz veins are nearly parallel to F_2 fold axes. They are filled by fibres which define a L_2 mineral lineation broadly orthogonal to F_2 fold axes.

In the ophiolitic nappe of Balagne, D_1 structures are deformed by centimetric to metric F_2 folds with considerable morphological variations (upright to overturned, close to largely open) and variations in orientation (Fig. 6). No cleavage has been observed in relation to these folds which thus formed at a very shallow structural level.

In the Santa Lucia Nappe, the D_2 structures are represented by pervasive S_2 cleavage (defined by phengitic micas and residual minerals) and F_2 folds (Fig. 5a). The F_2 fold axes define two orientations: NE–SW and NW–SE (Fig. 7) as it is also largely observed on the southern part of the Schistes lustrés (see below and Fig.

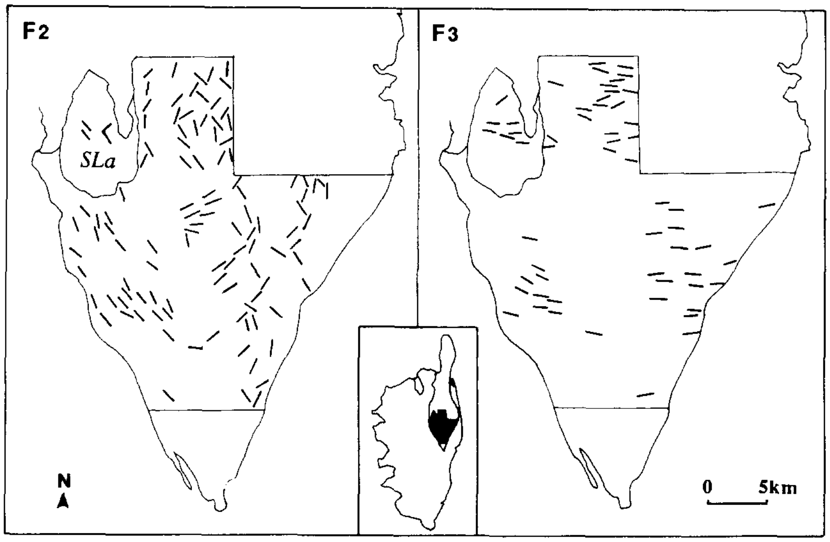


Fig. 8. Regional distribution of F_2 and F_3 fold axes in the southern outcrop of the Schistes lustrés (from Caron 1977, Scius 1981, Péquignot & Potdevin 1984) and in the Santa Lucia Nappe (SLa).

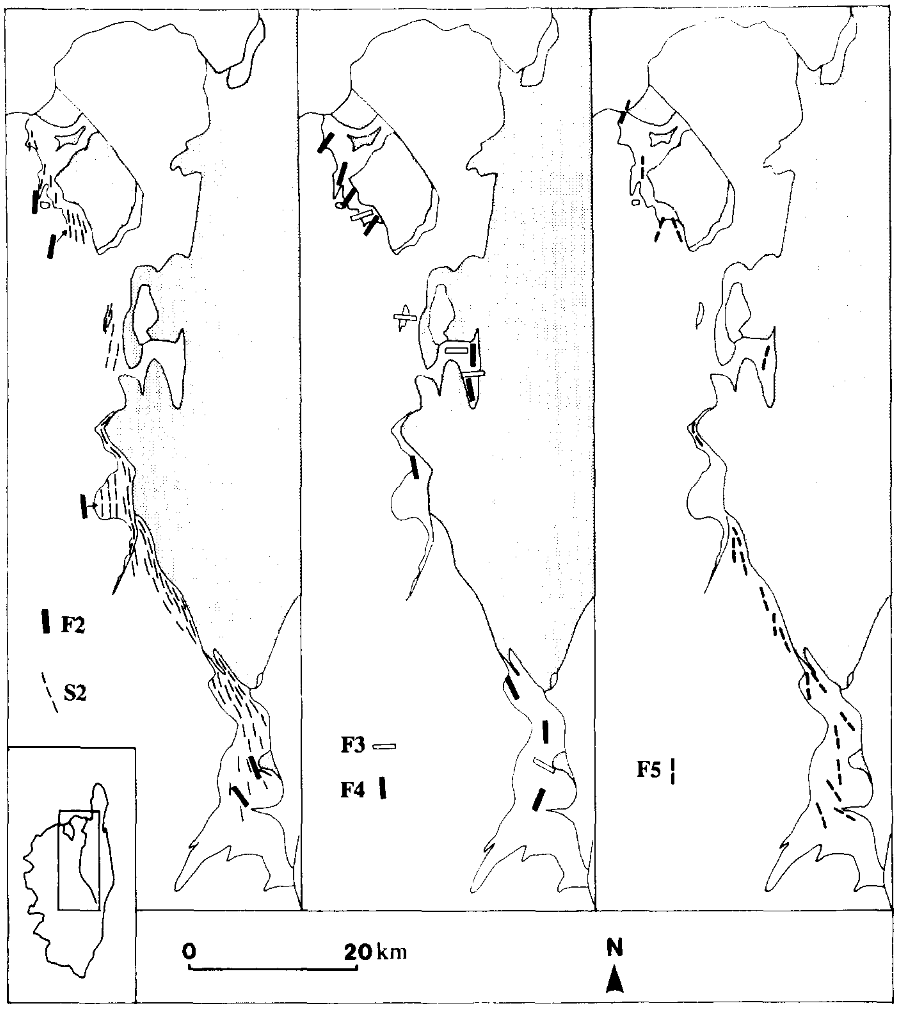


Fig. 9. Regional distribution of Alpine successive structures (F_2–F_5 fold axes, S_2 foliation trace) in the autochthon (Tenda Massif not studied).

8). These two directions are due to later folding by E–W third generation structures. The initial direction was probably NW–SE as we observe in the Narbinco Nappe of Balagne. The vergence of F_2 folds is unkown within the Santa Lucia Nappe.

The metamorphic conditions associated with the second generation structures are poorly determined in the Santa Lucia Nappe (Amaudric du Chaffaut & Saliot 1979). In the Balagne Nappe, the conditions during D_2 event correspond to shallow burial depths. This contrasts with the persisting deep conditions revealed in the internal units of the Schistes lustrés (Caron 1977, Caron *et al.* 1981, Péquignot 1984).

In the autochthonous domain, the earliest ductile structures distinguished are considered to be nearly contemporaneous with the second generation structures of the nappes (see above and Table 2); they are included within the regional D_2 deformation and labelled in this way (D_2, S_2, F_2). These structures are mainly represented by a regional S_2 cleavage or schistosity (depending of the structural level). They are irregularly developed (heterogeneous deformation) and are mainly located in front of the Alpine nappes (see cross-sections of sectors C and D in Fig. 4) and now steepened by subsequent tectonics. The S_2 foliation is associated with a stretching lineation and scarce sub-isoclinal to open F_2 folds (Fig. 5b). S_2 foliation and rare F_2 fold axes trend nearly parallel to the front of the Alpine nappes, i.e. NW–SE to N–S (Fig. 9). In weakly deformed zones, the dip of fold axial planes (Fig. 5b) and the bedding-foliation angles in non-folded terrains reveal a westwards vergence for these structures. In strongly deformed zones, rare drag folds (within the autochthon in the area of Corte, see also Bezert & Caby 1989) are in agreement with this westwards vergence. The dominantly E–W direction of the mineral lineation, defined by phengitic aggregates, elongated clasts (mainly quartz) and their pressure shadows is also compatible with a westwards vergence. However, shear criteria associated with D_2 deformation are poorly developed (local westward offsets of a microgranitic dyke by some S_2 foliation planes in granite located to the south-southeast of Venaco, few drag folds in metasedimentary rocks). Moreover, in these granites, some scarce and weakly developed (incipient) shear bands distinct from well-developed shear bands which post-date the foliation (see below), constitute two sets of conjugate bands apparently equally developed, suggesting a coaxial deformation regime. Thus, there are not enough arguments to associate D_2 deformation with thrust related bulk simple shear. However, the D_2 structures are nearly contemporaneous to T_2 thrusts because these thrusts, like the D_2 structures, are formed after Eocene deposits and are deformed by D_3 structures (see below). In addition, T_2 thrusts and D_2 structures both exhibit an externally directed vergence.

During D_2 regional deformation, the presently outcropping autochthon underwent maximum metamorphic conditions estimated at nearly 300°C/4 kbar (Egal 1989) or 320–410°C/4–6 kbar (Bezert 1990).

Third generation structures

These structures occur frequently in the Santa Lucia Nappe but are irregularly distributed in the autochthon domain (Fig. 9) and are not clearly displayed in the Balagne nappes. These structures mainly consist of E–W-trending F_3 folds (Figs. 5c, 7 and 9), associated with local reverse faults and axial plane cleavage poorly developed in autochthonous units but pervasive in the Lower Senonian flysch of the Santa Lucia Nappe. The folds have short limbs and are steeply inclined in the autochthon and gently inclined or recumbent folds in the Santa Lucia Nappe (Fig. 5c), with vergence either to the north or to the south. In the Santa Lucia Nappe, these folds often exhibit on their limbs a strongly developed E–W-stretching lineation, mainly defined by elongate quartz grains in sandstones, which is very often parallel to fold axes but occasionally oblique to them.

The significance of E–W-trending third generation structures is not clear. In the northern outcrop of the Schistes lustrés, E–W F_1 folds have been related to progressive westward shearing and thrusting (Mattauer *et al.* 1981, Harris 1985a,b). However it seems unrealistic to propose this for the F_3 E–W folds described in this paper as these folds are observed in weakly deformed units such as the parautochthonous Sant Angelo unit. In the southern outcrop of the Schistes lustrés, D_3 structures (see below) are nearly contemporaneous with an exhumation and a thermal re-equilibration, under greenschist facies conditions, of previously deep-seated units (Caron 1977, Péquignot 1984). However the precise structural significance of D_3 structures is still unknown.

Fourth generation structures

These structures are mainly N–S- to NW–SE-trending except in the autochtonous Eocene terrains of Balagne where their trend varies from N030 to N045 (Figs. 7 and 9). These structures include upright to steeply inclined (to E, NE or SE) F_4 folds (Fig. 5d), with axial-plane cm-spaced S_4 crenulation cleavages. The folds are present with similar characteristics in both autochthonous and allochthonous units, from a millimetric to kilometric scale. The syncline and anticline formed by the Santa Lucia and the Sant Angelo units correspond to F_4 folds which deformed T_2 thrust planes (see cross-section D in Fig. 4). Local westward-dipping reverse faults (Minor backthrusts), along which the granitic basement emplaced upon Eocene sediments are contemporaneous with these folds. The D_4 event is also responsible, at least in part, for the frequent steepening (at the front of allochthonous units) of previous anisotropy surfaces (bedding, foliation) (see cross-sections B, C and D in Fig. 4). In addition, in autochthonous granites located south-southeast of Venaco, some conjugate reverse decimetric-long shear zones, striking to the north (Fig. 5e), which are clearly later than the schistosity (S_2 regional foliation) as they are also observed in very weakly deformed granites, are associated with fourth generation deformation. No notable metamorphic transformations are associated with fourth generation structures.

The D_4 structures reveal an E–W shortening clearly after the major nappes stacking phases (T_1 and T_2). In addition, the D_4 structures do not deform Miocene rocks. Contrary to the previous descriptions by authors Durand-Delga (1978, 1984), Caron & Bonin (1980), Rossi *et al.* (1980) and Gibbons *et al.* (1986), the Miocene strata in Nebbio and Francardo areas do not define symmetrical synclines (of D_4 type) but are mainly E-dipping and only locally towards the west. We relate this geometry to synsedimentary tilting resulting from the progressive opening of the Miocene basins (Caron & Egal in preparation).

The structures of generations 2, 3 and 4 deform Middle Eocene units but not the Lower Miocene ones, so they formed successively during Late Eocene to Oligocene interval (Table 2).

Fifth generation structures

Open to tight F_5 folds with axial planes which are subhorizontal or dipping slightly toward the west or the east (Fig. 5g) represent the fifth generation of structures. They are associated with an S_5 crenulation cleavage (Fig. 5f) defined by residual opaques minerals, locally pervasive and mm-spaced. These structures are frequent in the autochthonous domain (Fig. 9) and in the Santa Lucia and Balagne nappes.

F_5 folds generally exhibit a nearly symmetrical form and are preferentially developed where folded surfaces were initially steeply dipping (Fig. 5g) No mesoscopic thrust planes are associated with these F_5 folds and S_5 cleavages. Thus, the D_5 structures express a vertical shortening. The axial direction of F_5 folds depends on the previous orientation of the folded surface.

Miocene formations are affected by structures whose geometry allows them to be assigned to the fifth generation of structures described above (Egal 1989): in the area of Francardo (Fig. 1), Lower Miocene formations exhibit, at their base, a subhorizontal dissolution cleavage which clearly cross-cuts the westerly-dipping bedding (Fig. 5h). In the Middle Miocene basin of Saint-Florent (Nebbio area, Fig. 1), these nearly horizontal structures are locally represented by stylolitic joints also cross-cutting the westerly-dipping beds. Consequently, the late ductile structures of Corsica are, at least in part, later than the deposition of Lower and Middle Miocene formations.

Late Alpine structures are also represented by brittle or ductile mesoscopic normal faults (Fig. 5i), N-trending and moderately to steeply-dipping (30–65°) to the east or more scarcely to the west. These faults, observed in autochthonous and allochthonous units (see also Jourdan 1988, Waters 1990), appear to be partly contemporaneous with and partly later than D_5 folds and cleavages (Caron & Egal in preparation).

Fifth generation ductile structures clearly post-date nappe emplacement since late S_5 cleavages deform Miocene deposits which rest unconformably upon the major thrust contacts (Fig. 1). There is thus no argument to relate the D_5 structures to tectonic loading resulting from nappe emplacement.

In orogens, the youngest structures often indicate crustal extensional thinning subsequent to earlier thickening by nappe stacking (e.g. Malavieille 1987, Seguret *et al.* 1989). Evidence for extension is provided within the studied area by mesoscopic normal faults. The last ductile structures (D_5) of Alpine Corsica present a geometry and a chronological position consistent with a bulk vertical thinning in an extensional context. We thus propose that the F_5 mesoscopic structures resulted from extensional tectonics. The extension involved could probably be accommodated by major low-angle (detachment) faults which would be responsible of the formation of late orogenic Miocene basins (Caron & Egal in preparation).

COMPARISON WITH STRUCTURAL FEATURES PREVIOUSLY REPORTED IN ALPINE CORSICA

The structural results presented in this paper are briefly compared below with those reported in the southern and northern outcrops of the Schistes lustrés. Within the southern Schistes lustrés, four generations of ductile structures have been distinguished (Caron 1977, Scius 1981, Péquignot & Potdevin 1984). With respect to their chronological position, they present similar features to the four generations described in this paper. In the southern Schistes lustrés, these structures are: N-trending D_4 structures E-verging; E–W F_3 folds (Fig. 8) thought to be S-verging; NE–SW or NW–SE (due to F_3 folding) F_2 folds (Fig. 8) whose initial vergence is assumed towards the northeast (Pequignot 1984); and D_1 structures initially N-trending and westward-verging (Caron 1977). This structural evolution is comparable with the major part of the evolution presented in this paper. However, the D_5 structures described in this paper have not previously been distinguished in the southern Schistes lustrés but have now been recognized there (Fig. 5i) and therefore probably were grouped with earlier structures by previous authors.

In the northern outcrop of the Schistes lustrés (NE Corsica), a late Eocene SE-verging tectonic episode and a mid-Cretaceous to Eocene? episode have been recognized (Mattauer *et al.* 1981, Harris 1984, Warburton 1986, Waters 1989, 1990). Concerning the latter, with the exception of Mattauer *et al.* (1981) who described only one major D_1 tectonic phase (but represented by three successive types of folds), two successive D_1 and D_2 deformation events have been distinguished (Harris 1984, Warburton 1986, Waters 1989). The D_1 structures are correlated by these authors to nappes emplacement (to the west then to the south-southwest according to Harris 1984) whereas either an eastward (Harris 1984, Waters 1989) or a southwestward (Warburton 1986) vergence is proposed for D_2 structures.

These results are partly consistent with those presented in this paper. Hence the Late Eocene structures recognized by the authors in NE Corsica, exhibit the same SE-vergence as the D_4 structures reported above in the neighbouring area of Balagne and thus probably represent the same tectonic event. The E–W D_3 structures described in this paper have seemingly not been recognized in NE Corsica. This could be explained by the irregular development of these structures. The D_2 and D_1 events distinguished, on the one hand in NE Corsica (Harris 1984, Warburton 1986, Waters 1989) and on the other hand in this paper, are likely equivalents because of their chronological position. However, the vergence of the D_2 structures is directed to the Alpine hinterland according to Harris (1984) and Waters (1989) as is proposed in the southern outcrop of the Schistes lustrés. This is in opposition to the D_2 westward-vergence found in the external Alpine zone (this paper). We thus assume a variable vergence for D_2 structures.

Abundant extensional structures have recently been reported in Northern Alpine Corsica (Jolivet *et al.* 1990, Fournier *et al.* 1991) and are probably related to the extensional tectonic stage distinguished in this paper.

So, despite differences, the structural features previously reported in Alpine Corsica are not drastically inconsistent with those in the autochthon and the Balagne and Santa Lucia nappes described in this paper.

CONCLUSION: STRUCTURAL AND TECTONIC EVOLUTION OF ALPINE CORSICA

In this part, the successive structures presented above are integrated into a proposed scheme for the Alpine evolution of Corsica.

The Eoalpine obduction and the D₁ *pervasive structures*

The early emplacement of Ligurian ophiolitic nappes (T_1 thrusting event) onto the European continental margin (obduction) occurred during Eoalpine (Upper Cretaceous) times. The first pervasive structures recognized in Alpine Corsica developed in the nappes during the same period (slightly prior, synchronously or just later that the obduction, according to different authors) while the visible part of the autochthon was not yet affected by ductile deformation (with the exception perhaps of the Tenda Massif).

Deposition of the Eocene cover

After the Eoalpine emplacement of the ophiolitic units onto the European margin, Eocene sediments were deposited in foreland basins upon the contacts between Eoalpine nappes and the autochthonous continental domain.

Late Eocene–Early Oligocene (?) compressive tectonics (D_2 *deformation event)*

After its deposition, the Eocene cover and its composite continental and oceanic substratum were imbricated by T_2 thrusts during the last important thrusting event in Corsica. These thrusts which towards the north of Corsica display increasing magnitudes of displacement reactivated the basal shear zones of the ophiolitic nappes. This thrusting is broadly contemporaneous with the pervasive D_2 deformation event. This tectonic event affected the present autochthonous outcrop where the deformation is strongly heterogeneous and located in front of the Alpine nappes. The D_2 structures have vergence which defines a fan-like regional structure. Thus tectonic stage probably occurred during the Late Eocene to Early Oligocene times.

Oligocene (?) compressive tectonics (D_3 *and* D_4 *deformation events)*

After nappe stacking events, Alpine Corsica was deformed during the Oligocene by E–W D_3 structures, partly associated with uplift and thermal re-equilibration of the tectonic pile. Subsequently, the (E–W) horizontal crustal (lithospheric) shortening continued in Corsica during Oligocene and was then mainly accommodated by F_4 folding (mainly N–S to NE–SW folds) and local backthrusting towards the east and southeast. This shortening occurred while Corsica began to separate from Europe (rifting stage: 35–24 Ma, see Genesseaux *et al.* 1989).

Miocene extension

During Lower and Middle Miocene, while rotation of the Corsica–Sardinia block ended (drifting stage: 24–18 Ma, see Genesseaux *et al.* 1989), compressive tectonics ceased in Corsica which then underwent extension accommodated by vertical shortening (F_5 folds), mesoscopic and crustal (?) normal faults and by the formation of clastic sedimentary basins.

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