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A structural geologic traverse through the Northern Apennines from Rapallo to Bettola (N. Italy)

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Abstract

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Four nappes have been distinguished in the Ligurian units of the N. Apennines between Rapallo and Bettola.

The uppermost Antola Nappe is non-metamorphic. It contains a rock sequence of distant origin, that has been folded during one single phase of deformation.

The immediately underlying Lavagna Nappe shows signs of very low-grade metamorphism. The constituent rock sequences originate from the Internal Ligurian Basin and have been subjected to polyphase folding and thrusting. Contrary to all later folding, the first folding phase (F_1) produced large-scale isoclinal folds that originally had a SW facing. These seem to have formed in an accretionary wedge, associated with a NE inclined subduction zone.

The Mélange Nappe underlies the Lavagna Nappe. It is non-metamorphic in the area studied and contains rocks from the Bracco Zone (Ridge) and the External Ligurian Basin. Synsedimentary deformation is common in the Mélange Nappe. This nappe is also characterized by the occurrence of large-scale isoclinal recumbent folds with a NE facing. Together with gravitational sliding and spreading phenomena, this isoclinal recumbent folding seems to have been coherent with the gliding of the rock sequences, now incorporated in the Mélange Nappe, off a NE slope.

The Canetolo Nappe is the lowermost thrust unit treated in this paper. It is non-metamorphic and the constituent rocks originate from the Subligurian Basin. After one phase of internal folding, the Canetolo Nappe was coupled together with the earlier stacked nappes. This pile of nappes overthrust the Tuscan units in a NE direction.

Introduction

The Northern Apennines (Fig. 1) stretch between the Anzio-Ancona line in the south and the Sestri-Voltaggio line in the north.

On stratigraphic and tectonic grounds the Northern Apennines are divided into Romagnan-Umbrian, Tuscan and Ligurian units (Sestini 1970, Squyres 1975, Dallan Nardi & Nardi 1975) (Fig. 1).

The autochthonous to para-autochthonous Romagnan-Umbrian sequences occupy the most external (E-NE) position. They are composed of a

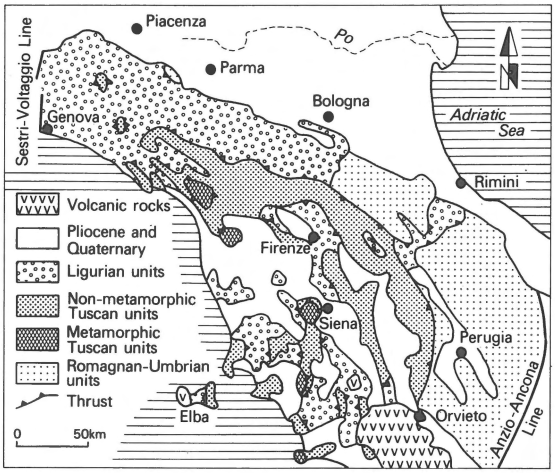


Fig. 1. Schematic tectonic map of the Northern Apennines.

calcareous Mesozoic to Paleogene lower part, covered by Miocene terrigenous clastics with turbiditic sandstone (= Marnoso-arenacea) and shallow-marine to continental sediments of Messinian to recent age.

The Tuscan units comprise a non-metamorphic Tuscan Nappe on top of a low-grade metamorphic lower unit. This lower unit crops out in a series of tectonic windows (the Apuan Alps, Mt. Pisano, Montagnola Senese, etc., Fig. 1). The oldest Tuscan sequences have a pre-Late Carboniferous age (Dallan Nardi & Nardi 1975). Late Carboniferous, Permian and Early Triassic terrigenous clastics (a.o. the Verrucano) underly a calcareous Mesozoic sequence, with Norian Dolomites at its base. Calcareous sedimentation in neritic and pelagic environments lasted up to the Paleocene. After Eocene sedimentation of pelagic shales, turbiditic sandstone was deposited up to the Late Miocene (Macigno and Cervarola sandstones).

After its metamorphism (at least 11 Ma ago according to Dallan Nardi & Nardi 1975), the lower Tuscan unit has been overthrust, from the southwest, by the non-metamorphic Tuscan Nappe. To the east and northeast the Tuscan units overthrust the Romagnan-Umbrian sequences (Fig. 1).

The Ligurian units are composed of oceanic to sub-oceanic rockassemblages of Late Jurassic to Middle Miocene age (Sestini 1970, Squyres 1975, Elter 1972). They originate from the Ligurian part of the Tethys. The Ligurian units overthrust the Tuscan and Romagnan-Umbrian units in several phases. During thrusting an intensive differentiation occurred into several thrust sheets (Sestini 1970, Dallan Nardi & Nardi 1975, Squyres 1975, Reutter & Groscurth 1978). Some Ligurian units contain evidence of very low-grade metamorphism (Cortesogno & Venturelli 1978) and cleavage development (Pertusati & Horrenberger 1975).

The prime aim of this study was not to establish yet another subdivision of the Ligurian units, but merely to pay special attention to their internal stratigraphy and deformation. This should lead not only to conclusions regarding the lithogenesis of the constituent rocks and their paleogeographic relationships, but also elucidate the deformation history of the Ligurian tectonic units.

Method

For the study of the Ligurian units a traverse was chosen from Rapallo to Bettola (Figs. 2 and 4). Primarily, a stratigraphic study was made, both in the field and from the literature.

The delimitation of the thrust units we propose, was based upon deviations from the normal age sequence in superimposed sediments and the occurrence of shear contacts. From each individual thrust unit, the internal faulting, folding, cleavage development and metamorphism was studied. Standard methods were used in the field for the analysis of fold-geometry, overprint relations and connected cleavage developments. Microstructural studies were made from thin sections. For every thrust unit the deformation history was reconstructed. An attempt was made to correlate the deformation phases of different units. The structural geologic results have been compiled in the map of Fig. 4 and the geologic sections of Fig. 5. The main thrusts recognized in this study were traced beyond the area studied on the basis of existing literature (Fig. 2).

In this paper little attention has been paid to high angle faulting. Where orientations and directions are mentioned, these are related to the present situation. No geotectonic rotation of the Italian Peninsula has been taken into account.

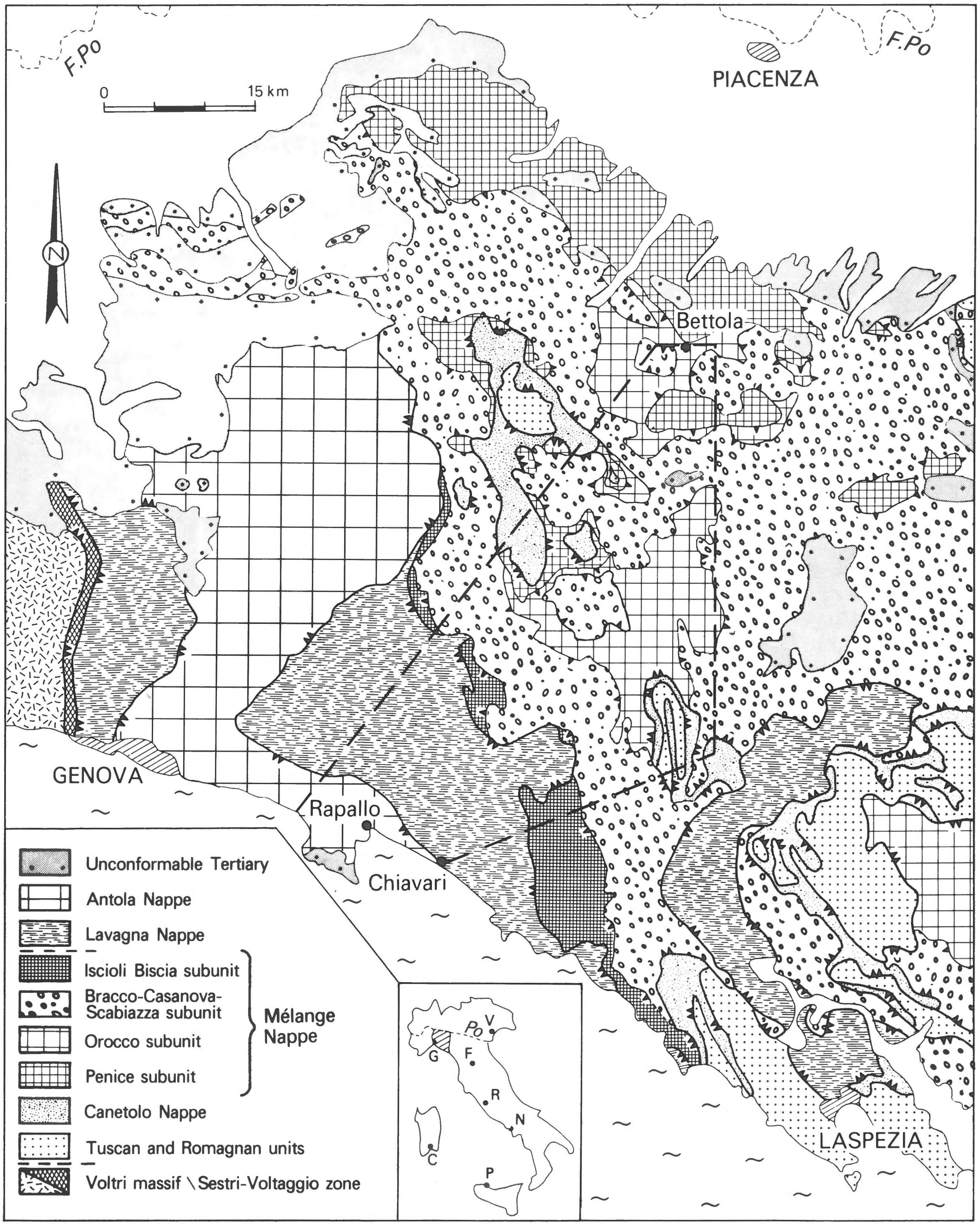


Fig. 2. Schematic structural geologic map of the northern part of the N. Apennines. For an explanation of the contact symbols, see the key to Fig. 4.

Stratigraphy and sedimentary history

Stratigraphic and structural geologic studies within the area enabled us to distinguish four nappes. In the order of their present superposition these are, from above to below: the Antola Nappe, the Lavagna Nappe, the Mélange Nappe and the Canetolo Nappe (Figs. 2, 3 and 4). The latter was observed to rest upon non-metamorphic Tuscan units in the Taro Valley (Fig. 4). Within the

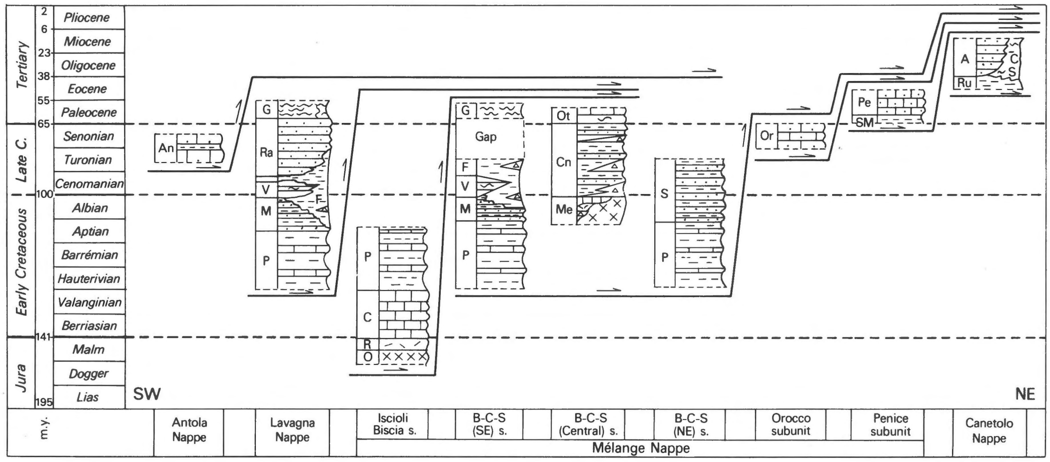


Fig. 3. Tectono-stratigraphic scheme of the thrust units within the region studied.

An = Antola limestone
O = Ophiolite
R = Radiolarite
C = Calpionella limestone
P = Palombini limestone and shale
M = Manganiferous slate or shale and siltstone
F = Forcella slate or shale and rhythmic siltstone
V = Verzi marl
Ra = Ramaceto sandstone
G = Giariette shale
Me = Mélange
Cn = Casanova sandstone and shale with olistostromes

Ot = Ottone limestone and marl
S = Scabiazza sandstone and shale
Or = Orocco limestone
SM = Santa Maria shale, sandstone and limestone
Pe = Penice limestone
Ru = Ruffinati siltstone
Cs = Coli Sanguineto siltstone and marl
A = Aveto Sandstone

B-C-S (SE) s.
B–C–S (Central)s.
B–C–S (NE) s.
The Bracco-Casanova-Scabiazza subunit in the southeastern, central or northeastern part of the region studied

Mélange Nappe four subunits have been recognized (Figs. 2, 3 and 4).

The Antola Nappe

Within the area studied, the Antola Nappe is entirely composed of the Antola limestone (Sestini 1970), a more than 1000 m thick sequence of turbiditic calcarenite beds, marl and shale. In calcilutitic parts, tracks of Helminthoïdes are found. The Antola limestone has a Turonian to Maastichtian age (Fig. 3).

Outside the area studied, the Antola limestone is often conformably underlain by the Montoggio shale (Sestini 1970). In its extreme NW extension, the Antola limestone is conformably covered by the Albirola formation (Sestini 1970) of Maastrichtian to Paleocene age. In this latter region, both the top of the Antola Nappe and its basal thrust are unconformably covered by Late Eocene to Early Oligocene sediments. No sedimentary relations are known between the rock sequence of the Antola Nappe and the stratigraphic units of underlying nappes. For this reason, the Antola Nappe is often considered to be of distant origin as compared with the other thrust units (Ten Haaf 1975).

The rock associations of the Lavagna Nappe and the Mélange Nappe have many indications of genetic interrelationship. Therefore, their stratigraphy and sedimentary history will be discussed together.

The Lavagna and Mélange Nappes

The oldest rock sequence was found in the *Iscioli Biscia subunit*, within the Mélange Nappe (Fig. 3). It is composed of Late Jurassic serpentinite, gabbro, diabase and pillow lava; with intercalations of spilite-gabbro breccias, ophiolotic sandstone and ophicalcite. The ophioliote massif is covered by radiolarite (Malm) and/or Calpionella pelagic limestone (Berriasian and/or Valanginian), which in turn is covered by Palombini pelagic limestone and shale (Hauterivian-Aptian) (Fig. 3). Slump

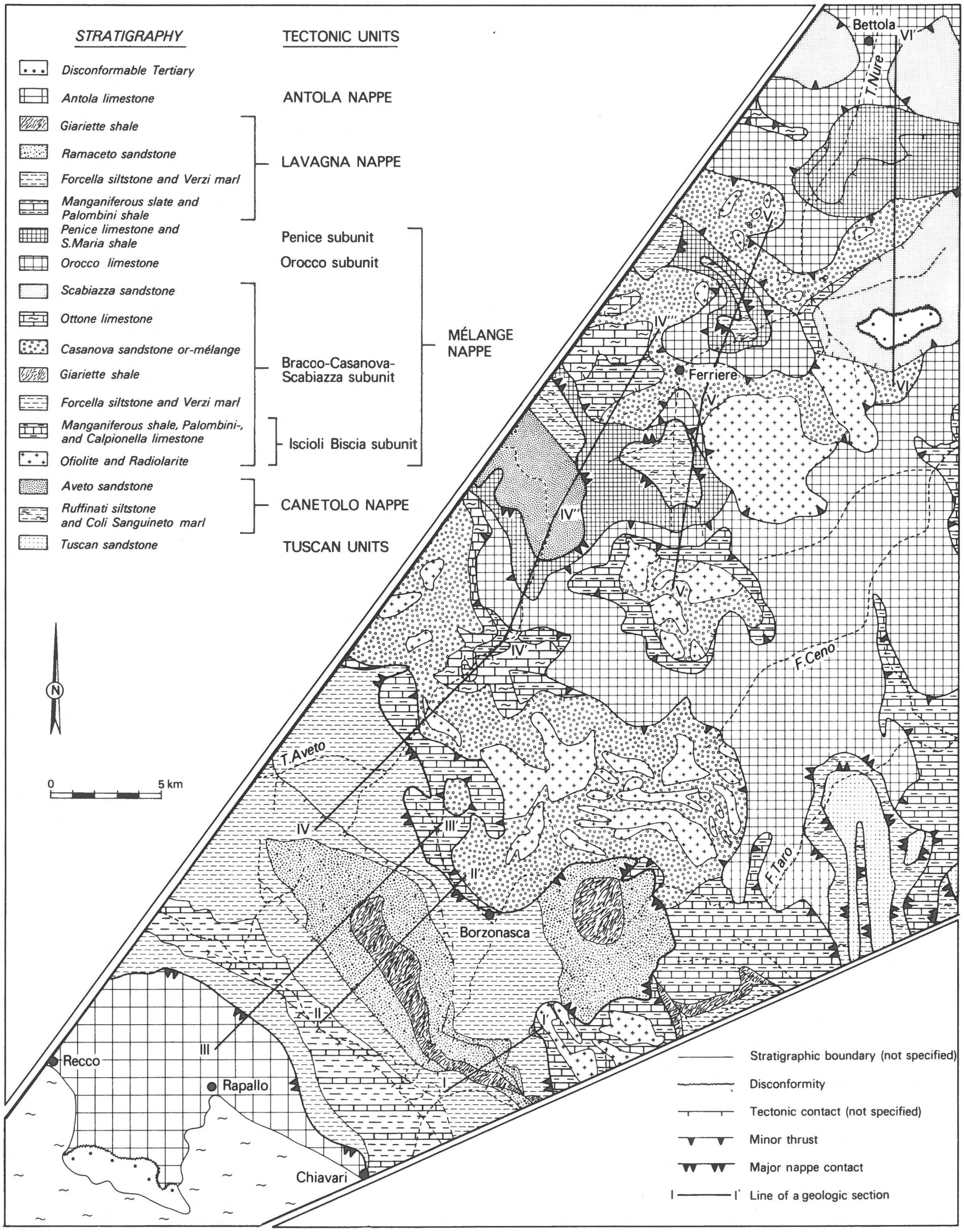


Fig. 4. Structural geologic map of the region from Rapallo to Bettola.

folds occur in the Palombini limestone and shale formation which, according to Naylor (1982) indicate slump movements in a SW direction.

In the Lavagna Nappe, which rests directly on top of the Iscioli Biscia subunit to the southwest (Figs. 2 and 3), the following sedimentary sequence was encountered from below to above (Fig. 3): Palombini limestone and shale (Hauterivian-Aptian); Manganiferous slates with siltstone and thin turbiditic sandstone beds (Aptian-Albian); the Forcella slates with thin-bedded rhythmic calcareous siltstones and few turbiditic sandstone beds

(Aptian-Late Cretaceous); the Verzi marl with slate and turbiditic sandstone beds (Albian?-Cenomanian); the Ramaceto formation with thick beds of turbiditic sandstone and shales (Late Cretaceous-Paleocene) and the Giariette shales (Paleocene). Intercalations of olistostromes, mainly consisting of angular components of Palombini limestone were found in the Forcella and Giariette formations.

In the *Bracco-Casanova-Scabiazza* (=B-C-S) *subunit*, directly underlying the Iscioli-Biscia subunit (Figs. 2 and 3), the original contacts between the formations are often poorly preserved. This is due to synsedimentary and post-diagentic mixing of the stratigraphic units, which resulted in the generation of mélanges. The term mélange is used here according to the definition of Naylor (1982).

Within the area studied, south of the Taro river (Fig. 4), the B-C-S subunit is composed of Palombini limestone and shale (Hauterivian-Aptian (Albian?), manganiferous shale and turbiditic sandstone (Aptian-Albian), Forcella thin-bedded rhythmic siltstone and Verzi marl (Albian-Late Cretaceous), and the Giariette shale (Paleocene) (Fig. 3, B-C-S (SE) s.). The lower boundary of the Giariette shale is a disconformity, which represents a break in the sedimentary column. The Ramaceto sandstone is absent. The Giariette shale is intensively slumped and contains many olistostromes with components of all older formations.

From the Taro river to the northwest, the lower part of B-C-S unit is composed of a mélange with slide blocks of different composition (Fig. 3, B-C-S (Central)s). The oldest rocks occur in rare olistoliths (up to 25 m) and are granites of 220-309 Ma. (Eberhardt et al. 1962). In the Mt. Aiona – Mt. Penna area, northeast of Borzonasca (Fig. 4), large ophiolitic components form by far the main part of this mélange. Huge slide blocks contain serpentinite, gabbro, diabase, pillow lavas and intercalations of ophiolitic breccias, ophicalcites and ophiolitic sandstone. These ophiolitic rocks have a Late Jurassic age and are genetically associated with radiolarite (Malm), some Calpionella limestone and Palombini limestone and shale (Neocomanian-Aptian). Olistostromes with angular components of the older formations which also occur in the Mélange have an Albian-Cenomanian age. Lateral and vertical transitions are found into the Casanova formation (Cenomanian-Maastrichtian) with black shale, turbiditic sandstone, olistostromes and ophiolitic slide blocks (Fig. 3). The terrigenous clastics in the turbiditic sandstone beds in the Casanova formation derive from the northeast according to Bertini & Zan (1974). The exotic slide blocks also came from the northeast according to Naylor (1982). The Casanova formation is conformably covered by the Ottone formation (Paleocene) with marl, turbiditic limestone beds and shale (Fig. 3, B-C-S (Central)s). To the northeast, this part of the B-C-S subunit extends from the 'Klippe' of Mt. Maggiorasca and Mt. Bue (Fig. 4 and Fig. 5, S part of section V) to the Ferriere and Bettola areas. Towards the Ferriere area the constituent stratigraphic units seem to be increasingly mixed. The mélange-nature of the original rock association may have been strengthened by later tectonic mixing.

Between Ferriere and Bettola a slab occurs, in which Palombini limestone and shale is conformably overlain by the Scabiazza formation (Albian-Turonian). This formation consists of turbiditic sandstone beds and shale (Fig. 3, B-C-S (NE) s). The Scabiazza formation is unconformably overlain here by sandstone and conglomerates (Fig. 4 and Fig. 5, section VI), which according to our determinations have a Middle Eocene to Late Eocene age.

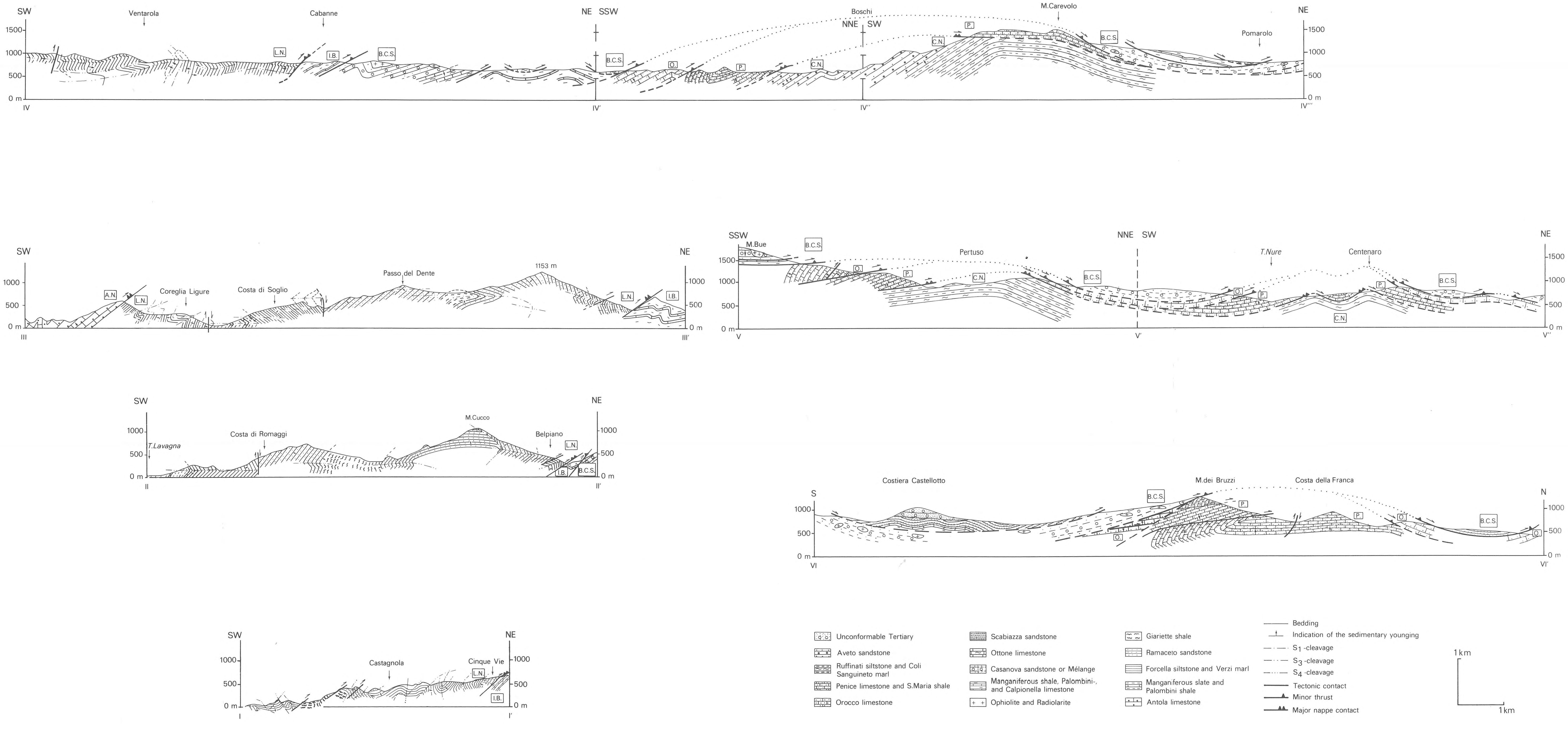
Just west of the area studied, Scabiazza sandstones are conformably overlain by a turbiditic limestone and shale sequences, called the Orocco limestone in this paper. It is equivalent to the Caio-, Cassio- and Bettola limestone formations of other authors (e.g. Sestini 1970).

The *Orocco subunit* is made up of the Orocco limestone, which contains nannoplankton, indicating a Senonian age. Southwest of Ferriere the Orocco formation contains many limestone beds. North of Ferriere more shales and marls are intercalated between the turbiditic limestone beds.

In the *Penice subunit* a basal sequence of shale with turbiditic sandstone and calcarenite (= S.

Fig. 5. Geologic sections. For their location see Fig. 4.

A.N. = Antola Nappe
L.N. = Lavagna Nappe
I.B. = Iscioli Biscia subunit
B.C.S. = Bracco Casanova Scabiazza subunit
O. = Orocco subunit
P. = Penice subunit
C.N. = Canetolo Nappe.



Maria formation, Lower Paleocene) is conformably overlain by the Penice formation, with turbiditic limestone beds, marl and shale (Fig. 3). These seem equivalent to the Farini d'Olmo limestone, the Sporno limestone and Dosso limestone of the other authors (Sestini 1970). The nannoplankton faunas we studied indicate a Paleocene to Middle Eocene age for the Penice formation in the area studied. Here, no sedimentary contact with older sediments was found. However, in the river Parma region, equivalents of our Orocco limestone seem to underly equivalents of our S. Maria and Penice formations. A sedimentary relationship between these turbiditic limestone formations, hence their sedimentation in a common basin, seems therefore highly probable.

Our palinspastic interpretation of the Lavagna Nappe and the Mélange Nappe strongly conforms to Elter's (1972) reconstruction of the Ligurian Basins. Fig. 6 is based upon his reconstruction for the Late Cretaceous. It shows the possible locations of the sedimentary realms, of the rock sequences in the Lavagna and Mélange Nappes. The important events that preceded and influenced this basin configuration will be summarized briefly (Fig. 6):

- Spreading processes, continental rifting and seafloor spreading, led to the development of a Ligurian Basin. Late Jurassic to Early Cretaceous formation of an ophiolite complex was followed by the sedimentation of radiolarite and/or pelagic Calpionella limestone and the Palombini limestone. Purely pelagic to hemipelagic sedimentation prevailed within the entire Ligurian Basin up to the Aptian.
- The first introduction of terrigenous clastics by turbidity currents and of olistostromes, indicates a change in tectonic activity, within the Ligurian Basin and its surroundings during the Aptian (Approx. 110 Ma ago).
- The development of a longitudinal ridge ('Zona' – or 'Ruga del Bracco', Elter 1972), indicates shortening caused by compressional forces perpendicular to the basin axis. From this ridge the sedimentary cover was partly or totally removed by sliding processes. The ophiolitic core of the ridge was deformed and tectonic breccias accumulated. The erosion products of the sedimentary cover and of the ophiolitic core provided the components of the olistostromes that were first intercalated in the sedimentary sequences both to the northeast and southwest of the ridge. Later continuous uplift, that affected wider areas adjacent to the ridge, led to widespread mélange formation during which also slide blocks developed. The 'Bracco ridge' caused the differentiation between Internal and External Ligurian Basins (Elter 1972).
- During the Late Cretaceous, turbidites deposited terrigenous clastics (the Ramaceto formation) in the Internal Ligurian Basin whereas turbiditic limestone (the Orocco formation) accumulated in the External Ligurian Basin.

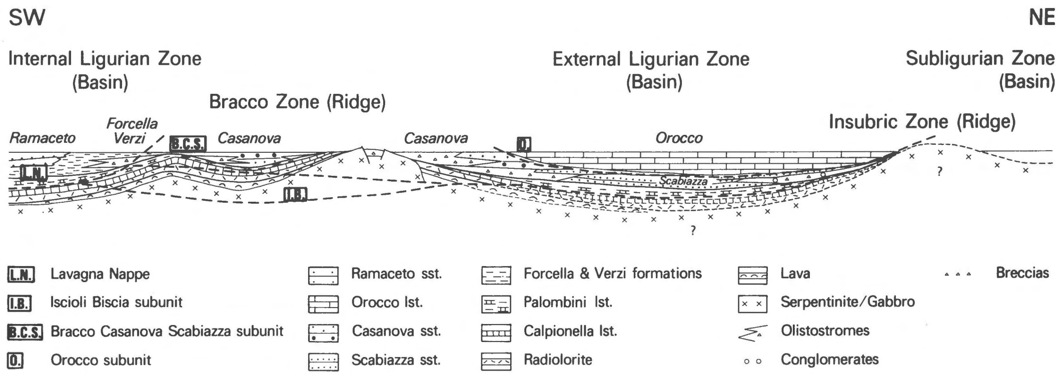


Fig. 6. Schematic reconstruction of the Ligurian Basins during the Late Cretaceous (After Elter 1972, with modifications). The presumed origin of the rock sequences of the Lavagna Nappe and the Iscioli-Biscia-Bracco-Casanova-Scabiazza- and Orocco subunits of the Mélange.

The olistostromes with Palombini limestone components in the Giariette formation prove that mass transport form a high (the internal part of the 'Bracco ridge') persisted during the Paleocene. In the Internal Ligurian Basin, sedimentation ended during that period. In the External Ligurian Basin sedimentation of turbiditic limestone (Penice limestone) ended during the Middle Eocene.

The Canetolo Nappe
In the area studied, this tectonic unit is composed of Ruffinati siltstone, Coli Sanguineto siltstone and marl and the Aveto sandstone (Fig. 3). In the siltstone and marl complex many slump horizons and olistostromes with shale and pelagic limestone beds ('Calcare e argille') are encountered. In the 'Calcare e argille' we found Middle – Late Eocene faunas. The Ruffinati siltstone furnished Middle Eocene – Early Oligocene faunas. In the Aveto Valley, the Ruffinati formation is overlain by the Aveto sandstone, and although the contact is tectonized, it is most probably of sedimentary origin. The Aveto formation contains turbiditic sandstone beds with much andesitic volcanic clastics and breccias and conglomeratic debris flows with metamorphic, magmatic and sedimentary components. It was not possible to reliably determine the age of the Aveto formation. The Coli Sanguineto formation possibly passes laterally into the Ruffinati and Aveto formations. It seems to be deposited more to the northeast and contains Oligocene – Early Miocene faunas (Den Haan 1979) (Fig. 3).

According to Elter (1972), the sediments of the Canetolo have been deposited in a 'Subligurian Basin', located to the northeast of the External Ligurian Basin and separated from it by the 'Insubric Zone' (or ridge) (Fig. 6). The olistostromes and debris flows, intercalated in the Canetolo sequence, most probably originated from this Insubric Zone. The Subligurian Basin would have been separated from the Tuscan Basin to the northeast by another elevated zone or ridge (Elter 1972).

Structural Geology

This section deals with the internal deformation of each thrust unit and its deformation history. Comparison of the deformational structures and correlation of deformation phases leads to conclusions as to the structural geologic history of the rock sequences in the region and the tectonics of the Ligurian units in general.

The Antola Nappe near Rapallo overthrusts the calcareous parts (Verzi marls) of the Lavagna Nappe. A more than 20 m thick tectonic mélange constitutes the thrust zone, which is inclined 40° to the southwest (Figs. 4 and 5, section III). Outside the area studied, the Montoggio shale often forms the base of the Antola Nappe, and much of the basal shear-deformation has been concentrated along slip surfaces in the argillaceous parts of the Montoggio formation. In such localities a tectonic mélange is absent. In the area studied, folds in the Antola Nappe only occur locally. They are slightly asymmetric open to tight folds with steeply SW inclined axial planes and a facing to the NE (Fig. 5,section III). Only one fold generation was found without cleavage development. Where Antola limestone overlies Montoggio shale, folding is conjugate (box folding; see for instance Marini & Terranova 1977). Drag folds, associated with shear at low angle to the bedding, are known from the lower parts of the Antola Nappe (Sestini 1970, p. 266, Fig. 5). No signs of metamorphism were found in the Antola Nappe. On a regional scale, the Antola Nappe overlies the Lavagna Nappe and the Mélange Nappe (Fig. 2). Moreover, the basal thrust appears to be undulating delineating gentle folds with wave lengths of more than 10 km. As the youngest sediments in the tectonic units directly underneath are of Paleocene age, and Late Eocene to Early Oligocene sediments unconformably cover the thrust contacts, thrusting of the Antola Nappe over the Lavagna and Mélange Nappes must have taken place since the Paleocene, and certainly before the Eo-Oligocene transition. The internal folding preceded or was contemporaneous with this thrusting; the large scale folding was later.

The Lavagna Nappe

This unit shows the most intensive, eutectonic deformation. In addition to faulting, polyphase folding and associated cleavages developed under very low-grade metamorphic conditions. In this paper, only a summary is presented of the structural features found in the Lavagna Nappe. Details will be described in a separate paper (Van Zutphen et al., in press).

- During phase F_1, very tight to isoclinal folds developed, with a slaty cleavage S_1. The latter often has a stylolitic, domainal character and it formed by pressure solution, and concomitant rotation of micas. F_1 folds have been observed on the scale of millimetres to kilometres. The horse-shoe structure of the Monte Ramaceto (Fig. 4 and sections II and III of Fig. 5) appears to be a huge SW facing F_1 syncline, overprinted by later folding. F_1 fold axes have a NW of SE plunge.
- Phase F_2 resulted in open folds with irregular sub-vertical axial planes. No F_2-related cleavage was found. In the Mt. Ramaceto and Mt. Cucco area, F_2 caused a domelike bending of the huge F_1 syncline (Fig. 5, sections II and III).
- Phase F_3-folds are open to tight and asymmetric in most cases. Especially in the hinge zones a cleavage, S_3, is developed as fracture cleavage or as crenulation cleavage. Microfolding, pressure solution and rotation of micas played an important role during S_3-cleavage development. From Fig. 5, sections II, III and S part of section IV it appears that S_3 usually is flat-lying. The long limbs of F_3-folds make an angle of 10°-20° with S_3. Mostly they show very few parasitic folds. On the other hand, the shorter steep limbs of F_3-folds always make a larger angle with S_3 (up to 90°) and they are deformed intensively by parasitic folds. F_3-folds were found on millimetre to kilometre scales. F_3-folds are approximately co-axial with the F_1-folds. The F_3 fold axes plunge northwest or southeast.
- Phase F_4 is characterized by local opend folds. Generally, very open F_4-folds produced slight undulations of S_3 and older structures (sections II, III and S part of IV, Fig. 5), and in such localities there is no cleavage associated with F_4. However, in the SE part of the region studied, F_4 is more obvious and cleavage may be found in the hinge zones (section I, Fig. 5). S_4-cleavages invariably are broadly spaced and steeply inclined to the southwest. Apart from the fold structures just described, boudinage structures and kink-folding was found. The latter is certainly post F_3.

According to Venturelli & Frey (1977) and Reutter et al. (1980) rocks of the Lavagna Nappe, within the region studied, have been subjected to very low-grade metamorphism. We used illite crystallinity to determine trends of the metamorphic grade within the Lavagna Nappe. A sudden change in illite crystallinity occurs along the so called Pagliaro fault, the northernmost internal thrust within the Lavagna Nappe (Fig. 4 and sections II, III and IV of Fig. 5). The rocks in the hanging wall have higher illite crystallinity than those in the foot wall, indicating that metamorphism occurred before the internal thrusting. This thrusting probably was assiociated with thrusting of the Lavagna Nappe over the Mélange Nappe, both of which are accompanied by tectonic mélanges. In the south, the Lavagna Nappe has been overthrust by the Antola Nappe. The thrust planes cut off all earlier fold structures in the Lavagna Nappe and they are undulating, due to gentle folding on the kilometre scale. These F_5-folds have steep axial planes, and there are indications that NW-SE trending folds and ENE-WSW trending folds were generated during this phase.

For reasons mentioned earlier, the Lavagna Nappe and Antola Nappe were mutually superimposed since the Paleocene and before the Eo-Oligocene transition. F_1, F_2, F_3 and F_4-folding and metamorphism developed prior to this thrusting, F_5 was later.

The four subunits of the Mélange Nappe have the following features in common:

- tight, NE facing recumbent folds of kilometre size;
- they show structural evidence for sliding and gravitational spreading.

The Iscioli-Biscia subunit, in the extreme SE part of the area studied (Fig. 4), appears to be intensely deformed eutectonically.

- During phase F_1, kilometre size, tight to isoclinal, recumbent folds were generated, with a NE facing. Cleavage is found only in the hinge zones. Thrusting at a very low angle to bedding is associated with these folds. F_1 fold axes plunge northwest or southeast.
- F_2-folds are open to tight and slightly asymmetric. In the hinge zones a cleavage may be found. This S_2 is commonly a crenulation cleavage and usually it is flat-lying. F_2-folds are approximately coaxial with F_1-folds in the Iscioli-Biscia subunit, and may attain centimetre to hectometre sizes.
- Phase F_3 resulted in the formation of gentle folds with wave lengths up to 10 km. No cleavage was found associated with this folding. It caused slight undulation of the axial planes of the F_1 and F_2 folds.

Thrust zones delimit the Iscioli-Biscia subunit to its upper and lower side. The basal thrust is a tectonic mélange, which may attain a thickness of more than 10 metres. The thrust zones are folded by F_3, but cut off the F_1- and F_2-folds within the Iscioli Biscia subunit.

The Bracco-Casanova-Scabiazza subunit contains a large variety of rock types that are often mixed by synsedimentary and eutectonic processes. In the area studied, south of the Taro river, F_1- and F_2-folds quite similar to those described from the Iscioli Biscia subunit were found. However, the fold axes are oriented NE-SW. This seems to be caused by a local rotation of the F_1- and F_2-folds, which probably originally trended NW-SE. Large-scale folding comparable with F_3 from the Iscioli Biscia subunit also was found in this part of the B-C-S sununit. Cleavage development is insignificant and seems to diminish in NE direction.

In the Taro river area, this part of the B-C-S subunit is overlain by the sedimentary mélange complex described earlier (p. 186) (see Fig. 4). In most cases, structural features are badly preserved in the mélange. They may be found only in the relatively undisturbed parts of the Casanova formation and in the larger slide blocks. Elsewhere, enormous slabs with overturned sequences occur (Mt. Aiona – Mt. Penna region and the Mt. Maggiorasca – Mt. Bue 'Klippe'). No hinge zones were found, but it seems quite possible that these overturned sequences originally formed the overturned limbs of large approximately isoclinal recumbent folds, comparable to the F_1-folds of the Iscioli Biscia subunit. Limited cleavage developments were only encountered in the S extremes of the B-C-S-subunit. To the northeast, the coherence between the constituent units decreases. During thrusting, fragmentation of the larger components and slabs was presumably followed by gravitational spreading. Thus the B-C-S subunit gradually lost its coherence and was transformed into a huge landslide ('frana orogenica') with a chaotic argillaceous groundmass that surrounded competent slabs.

The basal thrust of the B-C-S subunit is undulating, due to large scale folds (Fig. 5, sections IV, V and VI). In the region north of the Mt. Bue (S extreme of section V) these folds have ENE-WSW fold axes. The tectonic windows from Pertuso and Centenaro form parts of antiformal culminations, the unconformable Tertiary of Costiera Castellotto is a preserved remnant within a synformal depression of this large-scale folding (Fig. 5, section IV). It probably correlates with the F_3-folds of the Iscioli-Biscia subunit.

The Orocco subunit south of Ferriere is composed of a continuous slab of Orocco formation. The major part of this slab is overturned, probably by isoclinal recumbent folding, as was suggested for the B-C-S subunit. Here also, the hinge zones of the recumbent folds are missing, probably due to thrusting during folding (F_1). Hectometre sized open to tight folds with slightly asymmetric appearance and SW inclined axial planes (F_2) overprint these overturned sequences (see also Terranova & Zanzucchi 1982). North of Ferriere the Orocco formation is less calcareous and argillaceous intercalations are more numerous. There, clear evidence of internal shearing of the sequence is found, e.g. drag folding, tectonic imbrication, and thrust folding. Often, isolated slabs with folded limestone sequences were found, surrounded by sheared argillaceous material. On a regional scale, the Orocco subunit is discontinuous (see Fig. 5, sections IV, V and VI). Where the Orocco limestone overthrusts competent rocks (sandstones, limestones), tectonic mélange- and imbricate structures were found, together with ramping (see Fig. 5, sections IV, V and VI). Thrusting was in a NE direction. The basal thrust is undulating with large-scale folds with NW-SE and ENE-WSW folds axes.

The Penice subunit is characterized by discontinuous slabs with an upright orientation. Locally only hectometre- to kilometre sized folds occur. These are tight, asymmetric folds with SW inclined axial planes (see Fig. 5, sections IV and VI). The long, flat-lying limbs are hardly deformed, the steep limbs are cut by thrusts. No cleavage was found associated with this folding. There is much evidence for flexural slip. The basal thrust is accompanied by a tectonic mélange where the Penice subunit overrides competent rocks. This is the case between Boschi and Mt. Carevolo (Fig. 5, section IV), where the basal thrust cuts off all structures in the footwall. It is folded around NW-SE and ENE-WSW axes on a large-scale, like all other thrusts in the Mélange Nappe.

Summarizing, the chronology of the structured geologic events of the entire Mélange Nappe was:

- F_1, the development of large, NE facing, isoclinal recumbent folds, often accompanied by thrusting in NE direction;
- F_2, with asymmeytric, tight folds, with flat-lying to SW inclined axial surfaces. These folds may also have been accompanied by thrusting in NE direction;
- large-scale thrusting, with the generation of tectonic mélange zones. These cut all F_1- and F_2 structures, both in the hanging- and footwalls. Gravitational spreading processes were related to thrusting;
- F_3, large-scale gentle folding which may have been formed during two periods, one in which folds were formed with NW-SE fold axes, the other during which folds with ENE-WSW fold axes developed.

F_1, F_2 and thrusting may be genetically interrelated and could represent different stages of one single deformation process, the gravitatonal sliding of a huge rock sequence of a NE inclined slope. The sequences may have started to glide sometime during or after the Paleocene.

The Canetolo Nappe is relatively continuous. It has suffered gentle internal folding. The folds are asymmetric, open to tight, with steeply SW inclined axial planes and a NW facing (Fig. 5, section IV). Tectonic mélange zones accompany the upper and lower thrust. Drag folding was found in association with these thrusts, indicating a NW transport of the hanging walls. The thrusts cut all older folds in hanging- and footwalls. The thrusts are undulating in large-scale very open folds with ENE-WSW fold axes and NW-SE fold axes.

Since the youngest sediments of the Canetolo Nappe are of Early Miocene age, their thrusting by the Mélange Nappe must have occurred during or after this period. The internal folding of the Canetolo Nappe was prior to this thrusting. The large-scale folding was later.

Conclusions on the character and chronology of the regional structural geologic events

If the main thrusting of the Lavagna Nappe may be correlated with the thrusting processes within the Mélange Nappe, the chronology of the structural geologic events can be inferred to be as follows:

- From the Aptian onwards the Ligurian Basin experienced a compressional phase. This resulted, in first instance, in the generation of longitudinal culminations, and in the subdivision into Internal-, External- and Sub-Ligurian Basins (Fig. 6).
- The oldest eutectonic deformation structures described here, are found in the Lavagna Nappe. These are large-scale, originally SW facing, isoclinal folds (F_1, S_1). After insignificant folding of only local importance (F_2), a third period of folding generated open to tight folds (F_3, S_3) with flat-lying axial planes and strongly deformed steep limbs. During F_4, open folding with local

development of S_4 occurred. The rocks, now incorporated in the Lavagna Nappe were metamorphosed partly or entirely during the period while F_1-, F_2-, F_3- and F_4-folds developed.

- In a stage starting during the Paleocene and ending before the Eo-Oligocene transition, large-scale thrusting in a NE direction took place, leading to the mutual stacking of the Lavagna Nappe on the Mélange Nappe; and of the Antola Nappe on both the Lavagna Nappe and the Mélange Nappe (Fig. 2). Conjugate folding in the Antola Nappe, and NE facing isoclinal recumbent folding in the Mélange Nappe most probably accompanied thrusting. NE facing thrust-folding, ramping, mélange generation and gravitational spreading also must be attributed to this thrusting. Thrusting may have started during the Paleocene, the external parts of the External Ligurian Basin have not been overthrust before the M. Eocene.
- During or after the Early Miocene, the rocks now incorporated in the Canetolo Nappe were slightly folded (F_5). Hereafter, the pile of earlier stacked nappes overthrust the Subligurian domain (Fig.6). In turn the Canetolo Nappe formed and, coupled together with the earlier stacked nappes, overthrust the Tuscan units in a NE direction.
- Large-scale gentle folding, both around NW-SE axes (F6a), as well as around ENE-WSW axes (F6b), is the last deformation detected in this study. All older structures, formed in all thrust units, within the region, were overprinted by these folds.

Tectonic implications

All Cretaceous to Eocene tectonic events described above form part of the 'Ligurian Phase', whereas the Miocene and later events normally are attributed to the 'Tuscan Phase' of the Apennine orogeny (see e.g. Dallan Nardi & Nardi 1975).

In our opinion, the recognition of F_1, with large originally SW facing, isoclinal folds (normal limbs more than 15 km, overturned limbs 5-10 km), is of crucial importance for the understanding of the tectonics of the Ligurian Apennines. These large folds were originally SW facing and their axial planes (S_1) most probably were inclined 30°-40° NE. Some evidence has been found that the intensity of isoclinal F_1 folding within the Lavagna Nappe increases towards the SW with increasing metamorphic grade. This leads us to the hypothesis that these isoclinal folds formed in an accretionary wedge, associated with a NE inclined subduction zone. This subduction zone would have been situated southwest of the area from which the rocks of the Lavagna Nappe originate (Fig. 6). Subduction may have started sometimes during the beginning of the Late Cretaceous. Young oceanic crust (with an age of approximately 20-30 Ma at the start of subduction), with its thin sedimentary cover, subducted under the ophiolitic complex and sediments of the Internal Ligurian Basin (Fig. 6). The angle of subduction must have been relatively small, due to the low density of the subducting plate material. In the hanging wall of the subduction complex this caused imbrication with NE dipping thrust planes, adjacent to the subducting plate. Further northeast from it, SW facing isoclinal F_1 folding occurred in the rock sequences that were later incorporated in the Lavagna Nappe. F_1 folding gradually faded away in NE direction. The metamorphism in the Lavagna Nappe was most probably was also associated with the subduction. Within the accretionary wedge F_2 and later on the more important F_3, with approximately horizontal orientation of the S_3 developed. F_3 is clearly associated with gravity induced collapse folding.

The cessation of the subduction must have led to a general uplift of the region above the subducted plate, due to buoyancy. This uplift is believed to have been stronger in the SW and presumably resulted in a NE inclined slope, from which rock sequences slid in a NE direction. In the southwest, within the rock sequences that now form the Mélange Nappe, first huge NE facing isoclinal recumbent folds developed. This was followed by thrust-folding, thrusting, ramping, fracturing and gravitational spreading further downslope in a NE direction. At al later stage the Lavagna Nappe overthrust the SW parts of the Mélange Nappe. Further to the northeast, previously not folded sequences were gradually incorporated in the gliding rock masses, as these slid in NE direction. Overthrusting may have started in the Internal Ligurian Basin sometime during the Paleocene. It reached the external part of the External Ligurian Basin (Fig. 6) during or after the M. Eocene, and the Subligurian Basin not before the Early Miocene.

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