GEOLOGICA ULTRAIECTINA

mededelingen van
het Geologisch Instituut der Rijksuniversiteit
te Utrecht

No. 23

THE STRUCTURE OF THE WINDOW OF BOBBIO

(NORTHERN APENNINES, ITALY)

J.A. DEN HAAN

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(Northern Apennines, Italy)

PROEFSCHRIFT
TER VERKRIJGING VAN DE GRAAD VAN
DOCTOR IN DE WISKUNDE EN NATUURWETENSCHAPPEN
AAN DE RIJKSUNIVERSITEIT TE UTRECHT,
OP GEZAG VAN DE RECTOR MAGNIFICUS
PROF. DR. A. VERHOEFF, VOLGENS BESLUIT VAN
HET COLLEGE VAN DECANEN IN HET OPENBAAR
TE VERDEDIGEN OP WOENSDAG 31 OCTOBER 1979
DES NAMIDDAGS TE 2.45 UUR

DOOR

JULIUS ALBERT DEN HAAN
GEBOREN OP 13 APRIL 1946 TE EINDHOVEN

PROMOTOR: DR. E. TEN HAAF

Bobbio, panorama towards the south

Druk: Ordeman Rotterdam

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SUMMARY

Field work in the tectonic window of Bobbio has demonstrated the following tectonic units:

- Tuscan unit, the lowermost unit in the window. It is composed of a turbiditic sequence of Oligocene or Early Miocene age, folded into a large recumbent syncline with a gently NE-dipping NE limb and a steeply overturned SW limb.
  The Tuscan unit has been overridden from the SW by the
- Coli-Sanguineto Complex (CSC). This unit is composed of rocks in a sandy-marly facies and a chaotic shaly facies. The latter is interpreted as olistostromes, derived from the Monte Penice unit. The complex occurs in two areas between which the Tuscan unit crops out. We correlate the rocks of the areas upon their similar lithology and age, which is Late Oligocene or Early Miocene.
  Deformation along the CSC-thrust is dependent on the angle between the overthrust direction (from SW to NE) and the attitude of the beds in the relatively competent footwall. Where this angle is positive, a footwall syncline has been formed. Where it is negative, the footwall has been deformed by shear parallel to the beds and minor reverse faulting.
  We consider the so-called "Argilliti di Peli", which often crop out along the CSC-thrust plane, as a severely sheared level and not as a stratigraphic entity.
- The Ruffinati-Aveto unit. It includes two formations: Ruffinati Siltstone, which lithologically reminds of the CSC; its olistostromes are identical to those of the CSC.
  The Ruffinati Siltstone is stratigraphically overlain by the Aveto Sandstone. It includes andesitic tuffites, exotic conglomerates and turbiditic sandstones.
  The age of the formations could not be settled directly. There are indications for an Oligocene or Miocene age.

The Ruffinati-Aveto unit is only present in the SW part of the window. The contact with the CSC is tectonic; it is truncated by the overlying unit:

- The Monte Penice unit, which includes a sequence of dark shales (Santa Maria Shale) and a calcareous flysch (Monte Penice Limestone). The age of the formations is Paleocene-Eocene. The thickness of the unit varies strongly. It is locally absent.
- The Ligurid Complex is the highest Apenninic element.

In the investigated area, the total slip of these overthrusts exceeds 70 km. The movement have taken place in Miocene times. The unit of the Antola Limestone- a Helminthoid flysch- has overridden the Ligurid Complex from the W. It crops out W of the window of Bobbio. Since Late Eocene times it is welded to the Ligurian Alps, as shown the unconformable, continuous cover of the Tertiary Piemont Basin series. This entire block has been emplaced in its present position after -or in a late stage of- the completion of the Apenninic pile of thrust sheets. It is limited in the N by the E-W striking Varzi-Villalvernia lineament, a sinistral strike-slip fault. Its eastern limit is a N-S trending thrust front at the base of the Antola Limestone.

SAMENVATTING

Veldonderzoek in het venster van Bobbio heeft de volgende tektonische eenheden aangetoond:

- Toscaanse eenheid. Deze bevindt zich in de kern van het venster. Hij bestaat uit een merendeels turbiditische serie van Oligocene of Vroeg Miocene ouderdom die geplooid is tot een grote liggende syncline met een zwak NE hellende NE flank en een steil overkiepte SW flank.

  De Toscaanse eenheid is vanuit het SW overschoven door het
- Coli-Sanguineto Complex (CSC).

Deze eenheid is opgebouwd uit gesteenten in een zandig-mergelige facies en een chaotische schaleuze facies. De laatste wordt geinterpreteerd olistostromen, afkomstig van de Monte Penice eenheid.
Het complex komt voor in twee gebieden waartussen de Toscaanse eenheid ontsloten is. De gesteenten in deze gebieden worden door ons gecorreleerd op grond van hun gelijke lithologie en hun gelijke lithologie en hun gelijke ouderdom, t.w. Laat Oligoceen-Vroeg Mioceen.
De deformatie langs het CSC-overschuivingsvlak is afhankelijk van de hoek tussen de overschuivingsrichting (van SW naar NE) en de laagstand in het relatief competente onderblok. Waar deze hoek positief is heeft zich een onderbloksyncline gevormd. Bij een negatieve hoek treden in het onderblok laagparallelle differentiële bewegingen en kleine opschuivingen op.
De z.g. "Argilliti di Peli" die vaak langs het CSC overschuivingsvlak voorkomen worden door ons gezien als een sterk verwreven niveau en niet als een stratigrafische eenheid.

- De Ruffinati-Aveto eenheid. Deze is opgebouwd uit twee formaties:
  De Ruffinati Siltstone, die lithologisch verwant is aan het CSC; zijn olistostromen zijn identiek aan die van het CSC.
  Op de Ruffinati Siltstone ligt, met een stratigrafisch contact, de Aveto Zandsteen, die andesitische tuffieten, exotische conglomeraten en turbiditische zandstenen herbergt.
  De ouderdom van deze gesteenten kon niet rechtstreeks worden aangetoond. Er zijn aanwijzigingen voor een Oligocene of Miocene ouderdom.
  De Ruffinati-Aveto eenheid komt alleen in het SW deel van het venster voor. Het contact met het CSC is tektonisch. Dit alles wordt afgesneden door de overschuiving van de volgende eenheid:
- De Monte Penice eenheid. Hij bestaat uit een serie donkere

schalies (Santa Maria Schalies) en een kalkflysch (Monte Penice Kalksteen). De ouderdom van de formaties is Paleoceen-Eoceen. De dikte van de eenheid is zeer variabel. Locaal is hij geheel afwezig.

- Het chaotische Liguride Complex is het hoogste Apennijnse element.

Het totale bedrag van deze overschuivingen bedraagt in het werkgebied minimaal 70 km. De bewegingen voltrekken zich tijdens het Mioceen.

De eenheid van de Monte Antola flysch- een Helminthoidenflysch- heeft het Liguride Complex vanuit het W overschoven. Hij dagzoomt pal ten W van het venster van Bobbio. De eenheid vormt sinds het Laat Eoceen één blok met de Ligurische Alpen, zoals blijkt uit de samenhangende discordante bedekking door de tertiaire serie van het Piemonte Bekken. Dit blok heeft pas na -of in een zeer laat stadium van- de voltooiing van de Apennijnse dekbladstapel zijn huidige positie ingenomen. De noordelijke begrenzing is de E-W verlopende Varzi-Villalvernia lijn, een sinistrale zijschuiving; de oostelijke begrenzing wordt gevormd door een N-S verlopend overschuivingsfront aan de basis van de Monte Antola flysch.

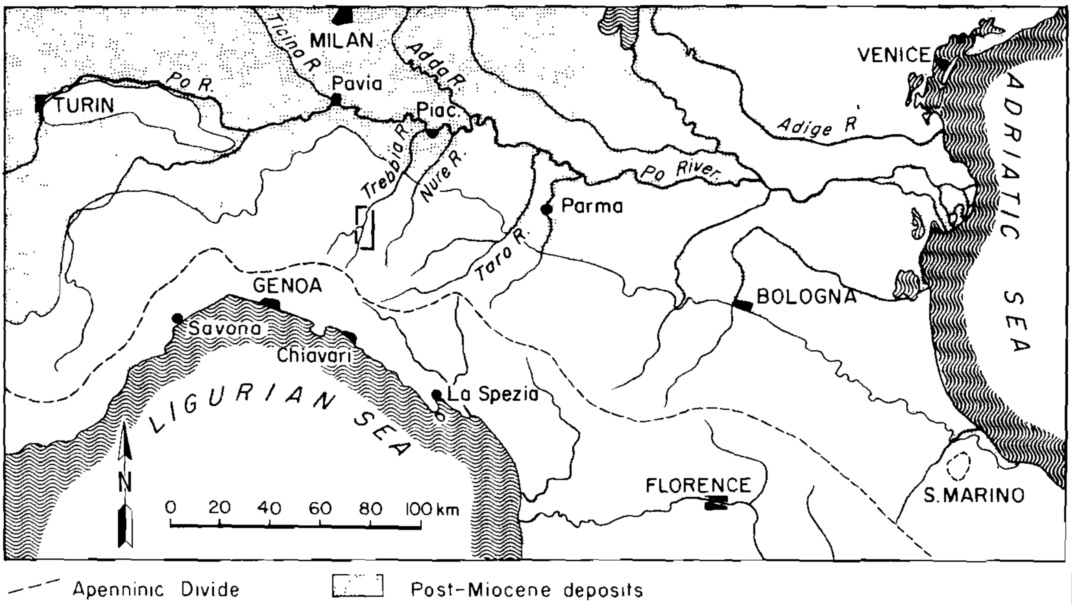


fig. 1 Map of NW Italy showing the location of the investigated area.

INTRODUCTION

1 General aspects

During the years from 1976 till 1978 field work was carried out in the window of Bobbio and adjacent areas. The window extends from Barberino to Ponte Lenzino, both in the Trebbia valley, and from the village of Torrio in the Aveto valley to the Aveto-Trebbia confluence (figs. 1, 2).

The main roads in the area are S.S. 45 della Val Trebbia (Genoa-Piacenza), S.S. 586 della Val d'Aveto (Marsaglia-Chiàvari) and S.S. 461 from Bobbio to Varzi, which crosses the Penice pass. Bobbio, the most important town, is situated on the left bank of the Trebbia at km 95 of S.S. 45 and has approximately 5000 inhabitants. Some villages are Marsaglia (S.S. 45, km 86) and Salsominore (S.S. 586, km 11).

Monte Penice (alt. 1460 m), Monte Sant'Agostino (1245 m) and the steep Aveto gorge, with sides rising up to about 600 m above the Aveto bed level are prominent topographic features. So are the beautiful meanders in the Trebbia gorges between San Salvatore and Marsaglia and between km 80 and 83 of S.S. 45.

Due to the heavy rainfall the vegetation is very dense, even on the steep slopes of the Aveto and Trebbia gorges. Therefore, it is convenient to carry out field observations in early spring when the trees are still bare and ground vegetation is not yet flourishing. Off the roads and paths, most of the field is badly accessible.

There are topographic maps of the area at scale 1 : 25.000 available in Piacenza and at the I.G.M. in Florence. These maps were found to be of excellent quality and partly highly up to date. We mainly used the sheets 71 II NE, 71 II SE, 83 I NE and 83 I SE. For exact indication of localities we have used the standard references given on the topographic maps. As these references are exact only to the nearest hundred meters additional numbers for location to the nearest ten meters have been added. The grid at the topographic map (fig. 2) serves for location to the nearest kilometer.

Aerial photographs were obtained from the I.G.M. The northern part of the investigated area is covered by photographs at scale approximately 1 : 33.000 numbered: F.71: S.22, 5913-5918; S.23, 7277-7282. Good detail is obtained with these photos. Those of the central and southern part of the area are at approximately 1 : 60.000; this makes them much less useful for our purposes. The numbers are: F.71: S.46, 1816-1819; F.83: S.47, 1076-1079; S.48, 1214-1216.

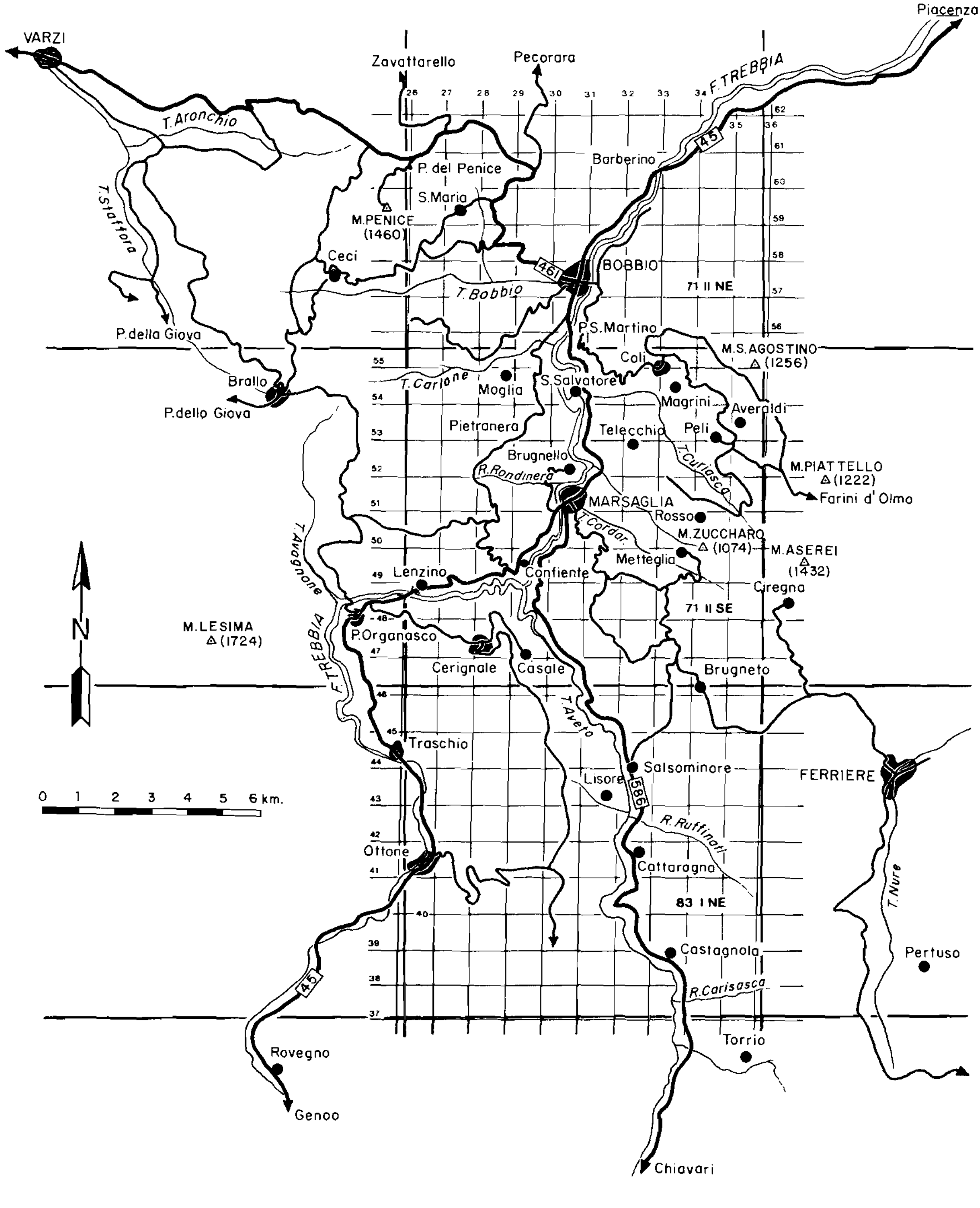


fig. 2 Topographic map of the investigated area.

Economy

Due to the absence of industry in the Trebbia valley down to the Po plain there is slight unemployment in winter. Farming is the most important means of support. Tourism is a rising branch: the Trebbia and Aveto valleys are known for their beauty. As there is no industry in the area, the waters are not polluted and fishing and canoeing are frequently practised recreation forms. Several springs of sulfurous water are to be found within the area. Of those, the thermal baths of Bobbio are the best known. Formerly, talcum was gathered from the extensive ophiolite outcrops; sweet chestnuts were collected in the large forests present in the area.

History of the region

Bobbio is an ancient town, situated on the old trading route from Piacenza to Genoa. The Iro-Scottish missionary Colombanus died here in the early 7^{th} century. He is still the patron of the town. A Benedict monastery was founded in Bobbio and in the Middle Ages the library of Bobbio became the most important one in Italy. Later, the Church removed it to the Vatican.
During the final stages of World War II the partizans founded the Republic of Bobbio: it lasted only a few weeks till the liberation of the area.

2 Aim of the research

The aim of the research was twofold:

a) to solve the structural and stratigraphic problems within the window of Bobbio and,
b) to find a solution to the problem which Ten Haaf (1975) calls the "Antola paradox".

Before going into details, it is convenient to review briefly the main structural and stratigraphic units, as they occur in the northwestern Apennines (figs. 3, 4).
The uppermost tectonic unit includes the Ligurid Complex, an eugeosynclinal series typified by the occurrence of ophiolites and of Helminthoid flysch. The age of the Ligurid sequence is Late Jurassic to Early Tertiary. The Ligurids have overridden the miogeosynclinal Tuscan sequence of which, in this area, only the sandstone top is exposed. The age of this sandstone top is not precisely known here, but it ranges from Early Oligocene to Middle Miocene. The sandstone is referred to as Macigno, Cervarola Sandstone and Monte Modino Sandstone. Its nearest outcrops to Bobbio are in the Taro window, 35 km toward the SE.

Between the Tuscanids and the Ligurids the Canetolo Complex is interposed. It consists of disconnected slabs the stratigraphy of which is badly understood. The best known rocks from the Canetolo Complex are the so-called Tertiary Alberese Limestone or Groppo de Vescovo Limestone and the chaotic "calcare e argilla".

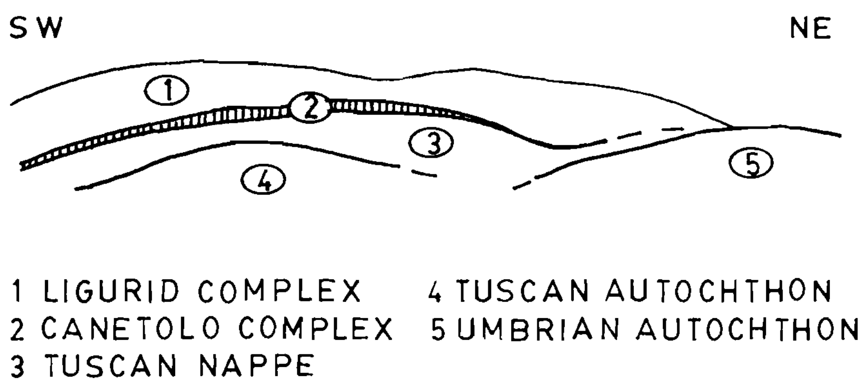


fig. 4 Schematic cross-section through the Northern Apennines from La Spezia to Parma, showing the superposition of the tectonic units. After Abbate and Sagri, 1970.

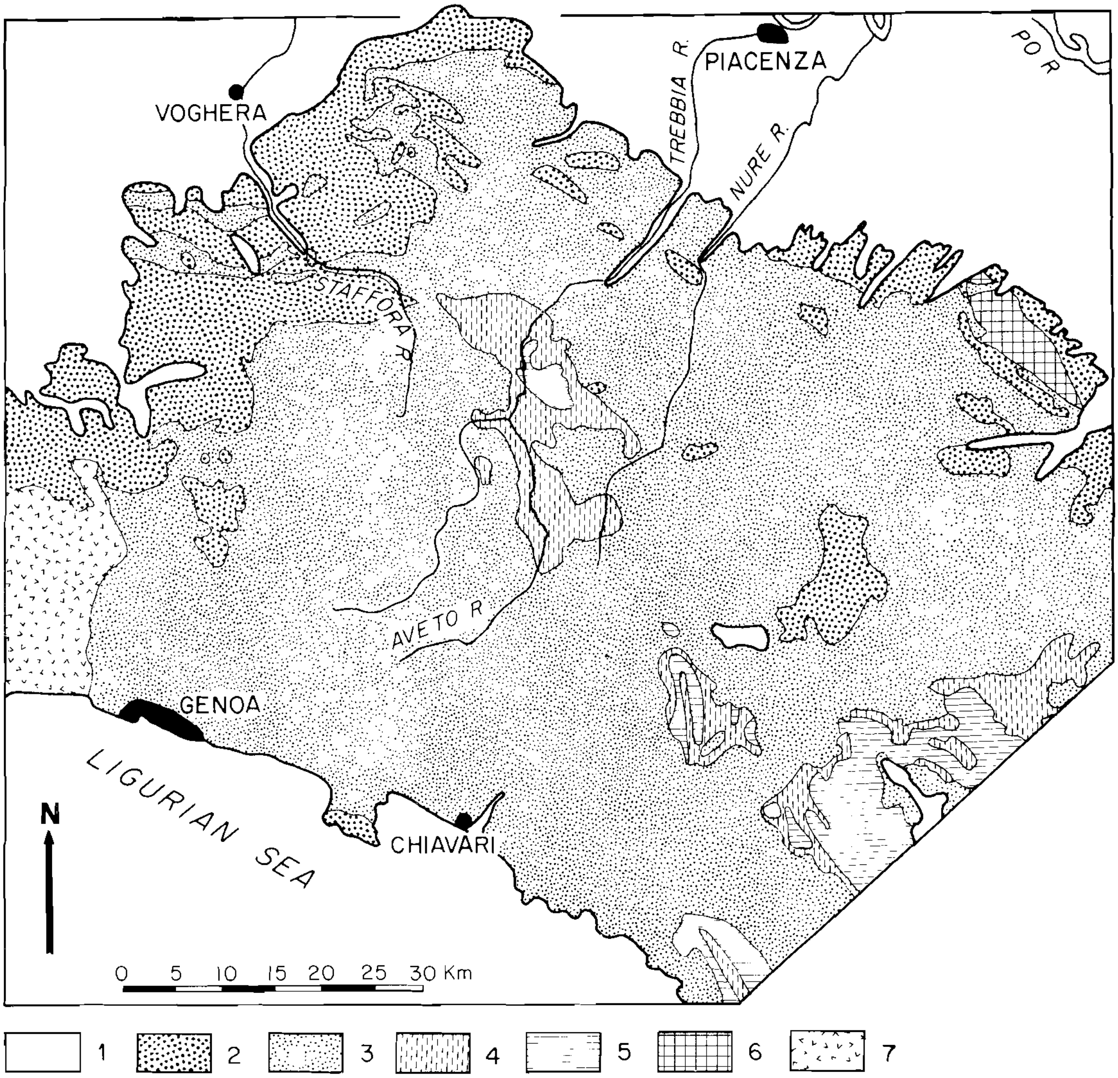


fig. 3 Simplified geological map of the most northwestern Apennines (after Sestini, 1970a). Legend:
1) Post-Miocene deposits;
2) Late geosynclinal sequences;
Eugeosynclinal sequences:
3) Ligurid Complex,
4) Canetolo Complex;
Miogeosynclinal sequences:
5) Tuscan sequence,
6) Umbrian sequence;

7) Voltri sequence.

Their age has been established as Paleocene to Lutetian.

The Helminthoid flysch, considered to be the top of the Ligurid sequence, is unconformably overlain by the Tertiary Piemont Basin sequence, made of often coarse-grained molassic deposits. The lowermost sediments of the sequence are of Late Eocene or Early Oligocene age. They not only overlie the Helminthoid flysch, but also the partly ultramafic Voltri Massif and the famous Sestri-Voltaggio lineament, reputedly the structural boundary between the Western Alps and the Apennines. Thus the Antola Limestone (a Helminthoid flysch), the Voltri Massif and the Tertiary Piemont Basin series are united into a single block since the Early Oligocene: the Antola-Voltri-Piemont block (A-V-P-block).

a) One of the aims of this study was to gain insight in the structural and stratigraphic relation of the Canetolo Complex and the Tuscan unit in the window of Bobbio.

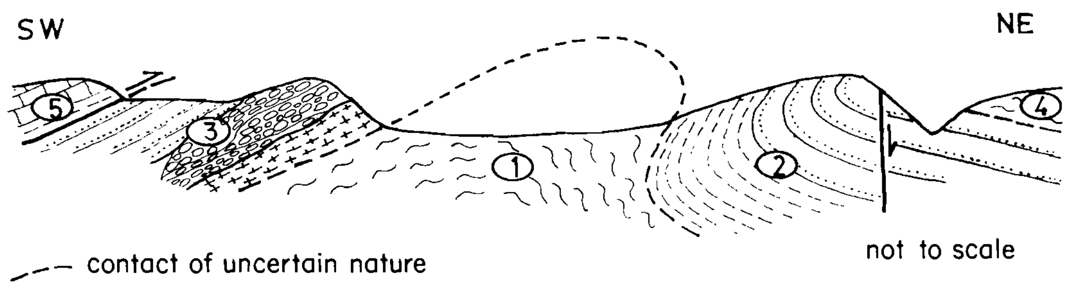


fig. 5 Schematic cross-section through the window of Bobbio, interpreted after Bellinzona, Boni et al. (1968):

1) Complesso di Sanguineto (Miocene prelanghiano-Oligocene)
2) Formazione di Bobbio (Langhiano)
3) Formazione di val d'Aveto (Langhiano)
4) Complesso di Coli (Langhiano ?)
5) Formazione di Monte Penice (Eocene medio-Paleocene)

The Tuscan sequence has been folded into a large recumbent syncline with an overturned SW limb. In the Aveto valley, more to the S, a thick sequence of green sandstones and conglomerates crop out. These sandstones were tentatively correlated with the Tuscan sandstones by Bellinzona, Boni et al. (1968). Thus a simple structure was created; an overturned anticline followed by an overturned syncline to the NE. The core of the anticline would be occupied by the Sanguineto Complex, while in the syncline the Tuscan sandstone is overlain by the Coli Complex which is very similar to the Sanguineto Complex. Many contacts are said to be of incertain nature and ages are often based upon lithological correlations or on supposedly stratigraphic successions (fig. 5).

In our opinion the Aveto- and Tuscan sandstones are quite different formations by their sedimentology and their composition. Previously, allochthony of the Aveto Sandstone had been proposed by Ten Haaf (1961).

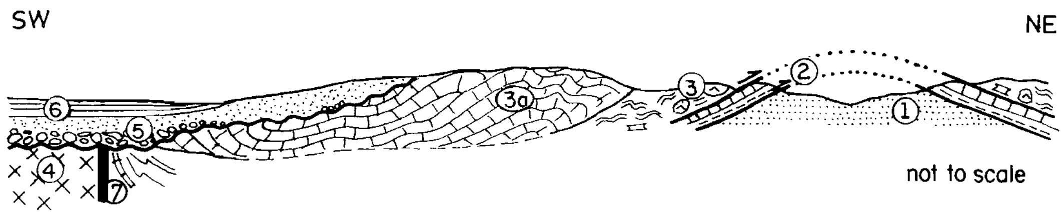


fig. 6 The Antola paradox: a cross-section through the implied units:

1) Oligo-Miocene rocks of the window of Bobbio;
2) Monte Penice sequence (Paleocene-Eocene);
3) Ligurid Complex;
3a) Antola sequence;
4) Voltri Massif;
5) Tertiary Piemont Basin series (Upper Eocene-Miocene);
6) Post-Miocene deposits.

If so, a tectonic contact must exist between the Aveto Sandstone and the Tuscan outcrops.

The striking resemblance between the Coli- and Sanguineto Complexes at both sides of the recumbent syncline of the Tuscan unit was another point that needed closer investigation.

b) The "Antola paradox" (fig. 6) implies the fact that Ligurid units have undergone vast lateral displacements after early Miocene times: in the window of Bobbio, Oligo-Miocene deposits have been overthrusted by the Ligurids. On the other hand, the Antola Limestone, considered to be a Ligurid flysch, and the Voltri Massif are both unconformably overlain by the Tertiary Piemont Basin series, of which the basal terms are of Late Eocene age. This implies that the Antola Limestone and the Voltri Massif cannot have moved independently after the Late Eocene. Another aim of the field work in this area was to find a solution to this highly unsatisfactory picture.

3 Historic review

In 1929 O. Ludwig published the first detailed report on the geology of the region near Bobbio. The author cited Taramelli (1916), Rovereto (1922-26), Sacco (1889, 1891, 1893, 1905, 1922), Steinmann (1907, 1913, 1925, 1926, oral comm.):

Taramelli distinguished three sequences, all of Eocene age:

3) A Helminthoid-bearing limestone-marl sequence;

2) Serpentines, ophiolites, granites and associated sediments;

1) Macigno sandstone with shales.

In a standard section S of Bobbio Rovereto distinguished two "Stufen":

- Lutetian, resting transgressively upon the Cretaceous Scaglia. It includes a Lower Sandy Flysch (Macigno), the nummulite-bearing Lower Calcareous Flysch and sediments with large ophiolite masses.

- Bartonian, also transgressive. It is composed of Upper Sandy Flysch with few ophiolites and the fucoid-bearing Upper Calcareous Flysch.

Sacco (1891) attributed the entire ophiolite-bearing sequence to the Mesozoic and emphasized this included the "argille scagliose". He was aware of tertiary sediments underlying mesozoic rocks but he explained this phenomenon with overturned fold limbs.

Steinmann (1907) first recognized the allochthonous position of the Ligurids (an ophiolitic sequence with calpionellid limestone and radiolarites) upon the Tuscanids, in which he included the Macigno and the "calcare e argilla" (= Kalk-Ton Serie). He considered the Tuscanids autochthonous whereas the Ligurid root zone was thought to be in the Tyrrhenian Sea.

Rovereto (1926) agreed with the concept of allochthony, but he placed the Ligurid root zone in the Adriatic Sea. His tectonic units were:

- autochthonous Eocene rocks near Genoa;
- a Tuscan complex with dome-shaped structures in Tuscany;
- a Tusco-Ligurid allochthon typified by ophiolites;
- a complicated Marche-Basilicata zone.

Ludwig (1929) followed Steinmann's concepts. He recognized the tectonic superposition of the ophiolitic formations upon a tertiary sequence consisting of Macigno, Kalk-Ton Serie and foraminiferous marly limestones (our Monte Penice Limestone). He considered the tertiary rocks autochthonous.

During the last three decades more allochthonous units have been recognized in Ludwig's autochthon.
In many places in the Northern Apennines the Ligurids appeared to be underlain by Paleocene and Eocene limestones and "calcare e argilla" (the Canetolo Complex). This Subligurid unit has been demonstrated in the window of Bobbio by Labesse (1963), Elter, Gratziu and Labesse (1964), Mutti (1964), and is usually called

the Monte Penice unit. The map by the Pavian geologists (Bellinzona, Boni et al., 1968) also figures the Monte Penice unit, limited by an upper and a lower tectonic contact, but for unknown reasons the word 'window' has been put between quotation marks in the title.

The relations between the remaining units will be discussed in this report. They are composed of rocks of Oligo-Miocene ages. The Tuscan core of the window (Macigno) has been described by Mutti and Ghibaudo (1972). In this sedimentological study the sequence is interpreted as the external part of a sediment cone at the lower end of a submarine canyon, transgressively overlying their substratum.

Exotic components of the conglomerates in the Aveto valley have been described by Roccati (1921), Rodolico (1941) and Aiello (1975). The granite-, metamorphic and ophiolite pebbles have puzzled geologists for decades. Green tuffites of the Aveto sequence are thought to have been derived from andesitic volcanism during Oligocene and Aquitanian times (Aiello, 1975; Wezel, 1977).

Most authors interpret the structure of the Tuscan core of the window of Bobbio as some form of an overturned anticlinal fold (Anelli, 1938; Mutti, 1964; Ten Haaf, 1961; Bellinzona et al., 1968), but Schlüter (1968) and Reutter and Schlüter (1968) explain the overturned zone as a curling-over of the margin of the Macigno (they say Cervarola Sandstone) basin by synsedimentary compression. They do not suppose the presence of an anticline. The authors argue that the degree of allochthony of the overlying units is considerably reduced with respect to other theories.

Some authors have correlated the Aveto sequence with the Tuscan sequence (Boni, 1961; Bellinzona et al., 1968) (fig. 5), others consider it parautochthonous (Kube, 1965; Schlüter, 1968). Allochthony of the sequence has been suggested by Ten Haaf (1961), Abbate and Sagri (1970), Plesi (1974, 1975, 1975[a]).

4 Classification of tectonic units

It appears that there is no common usage of terms like parautochthon, mesoautochthon, semi-autochthon etc. The Glossary of Geology of the A.G.I. (Gary et al., 1972), is not decisive either, as the use of some terms differs from terms used in Apenninic geology.

The definitions in the Glossary, cited litterally, are:

1) autochthon: a rock body that remains at its site of origin, where it is rooted to its basement;
2) allochthon: a mass of rock which has been removed from its original site by tectonic forces, as in a thrust sheet or a nappe;
3) parautochthonous: said of a rock body that is intermediate in position between allochthonous and autochthonous;

These definitions are quite clear. Confusion may rise with:

4) neoautochthon: a stable basement or autochthon formed where a nappe has ceased movement and has become defunct;
5) parallochthon: rocks that were brought from intermediate distances and deposited on or near an allochthonous mass during transit;
6) mesoautochthon: an autochthon or basement formed temporarily where a nappe has ceased movement, and on which the sediments of a parallochthon are deposited.

Definitions 5) and 6) imply that a mesoautochthon cannot exist without a parallochthon. A mesoautochthon may either be reactivated to an allochthon; in that case sediments deposited on it remain parallochthonous; else it is stationary and rocks deposited on it are neoautochthonous.

Italian geologists often use the term mesoautochthon instead of parallochthon to indicate the sediments deposited on top of a moving or intermittently moving allochthon. As a rule, the mesoautochthon is unconformably overlain by neoautochthonous sediments after the movement of the allochthon has ceased. This situation is referred to as "semi-allochthony" by Merla (1951), the first author to distinguish such a tectonic position in the Apennines. Therefore it is right and convenient to use his terminology (fig. 7).

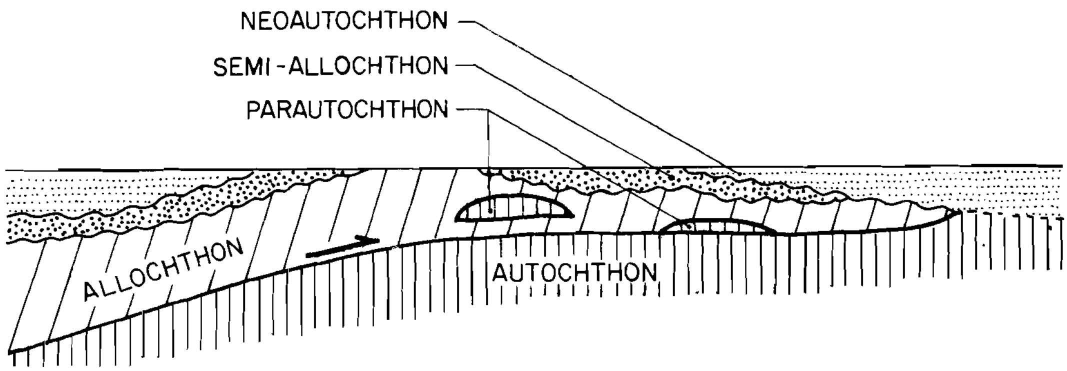


fig. 7 Nomenclature used in this report.

5 Morphology

There is a strong relation between the morphology and the geology. The Trebbia and Aveto rivers have cut deep valleys in the terrain, which is formed by outcrops of various tectonic units with diverging rock types:

The Ligurids are on top; they compose the elevated areas, although their rocks are commonly very plastic. The ophiolite masses stand out and form the summits. At several localities ophiolite blocks have been carried down by gravitational slides. The presence of such incompetent rocks as the Ligurids in elevated positions points to the relatively young uplift of the terrain by block faulting which still continues along the Padan margin.

The outcrops of the Canetolo Complex underlying the Ligurids are only prominent where the Monte Penice Limestone has been developed in a thick sequence.

This is especially so at Monte Penice, where the formation is extremely thick. In other localities the Monte Penice Limestone is exposed in small precipitous cliffs. It is conspicuous by its white colour. Often the lower slopes are mantled by rock waste; consequently, the transition to the underlying Santa Maria Shale cannot be studied.

The deepest parts of the river valleys are characterized by two different landscapes.

The tough rock types (San Salvatore Sandstone, Aveto Sandstone) stand out topographically and are cut by narrow and steep river valleys: construction of a dam has been started downstream San Salvatore but it has never been finished.

Quite a different landscape is formed by the plastic shales of the Coli-Sanguineto Complex, which crops out in the broad and open valleys near Bobbio and near Marsaglia-Sanguineto. The shale outcrops form gentle slopes which are used as meadows and arable land. The mobility of the shales after prolonged precipitation forms a major problem in the construction and maintenance of roads all over the Northern Apennines. It also greatly hinders geologic investigations because of the resemblance of landslides to the geologically intercalated shaly olistostromes and to the slided shales of "calcare e argilla" (fig. 8).

Outcrops of sandy and marly rock types protrude from the shales. They sometimes support and stabilize the shales in smaller stable basins or they may slide down with them. Most of the built up areas are situated on such firmer outcrops. In our opinion the eastern part of the village of Coli is in danger of sliding down.

The young morphology is especially conspicuous in the area W of the Trebbia and Staffora valleys, formed by outcrops of the Antola Limestone that reaches a thickness of 2 km. An undulating plateau at an altitude of 1500 - 1700 m has been incised by extraordinarily precipitous torrent gullies.

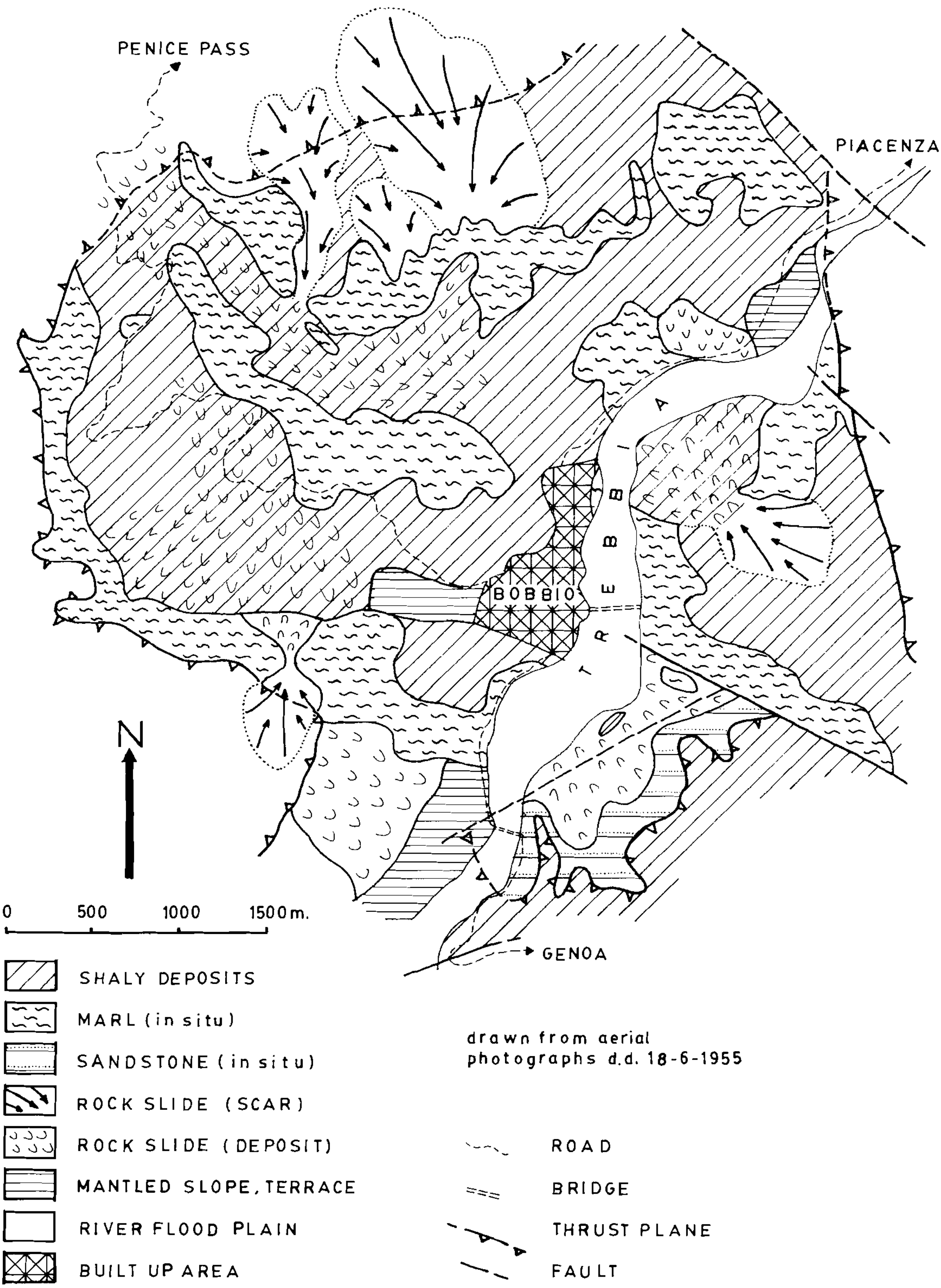


fig. 8 Morphological map of the Trebbia valley near Bobbio.
Note the intensive sliding of the shaly deposits.

II STRATIGRAPHY

6 Introduction

In the NW Apennines, stratigraphic relationships are in general either obscure or, at least, complicated. Most lithologic units are bounded by thrust planes or major faults; the thrust slabs comprise only small stratigraphic sequences. Consequently, tectonic considerations cannot be kept out of the stratigraphic descriptions. Therefore, the lithologies of the sequences should be described in their order of tectonic superposition rather than in the order of their, often unknown, ages.
The main units are (fig. 9):
- Tertiary Piemont Basin series;
- Antola sequence;
- Ligurid Complex;
- Canetolo Complex;
- Tuscan sequence.

- The Tuscan sequence.
  The core of the window of Bobbio is formed by the sandstone top of the Tuscan sequence. Its age is not exactly known but it is Oligocene or Lower Miocene.
- The Canetolo Complex.
  The Canetolo Complex overlies the Tuscan sequence and it underlies the Ligurid Complex. It is often referred to as Sub-Ligurid. It is a badly defined unit with Ligurid affinities comprising sediments of Paleogene and Miocene age. The Lutetian Monte Penice Limestone is an important formation of the Canetolo Complex. Younger units are composed of marl, siltstone, sandstone and conglomerate. These units have been dismembered to such a degree that their stratigraphy is only fragmentarily known.

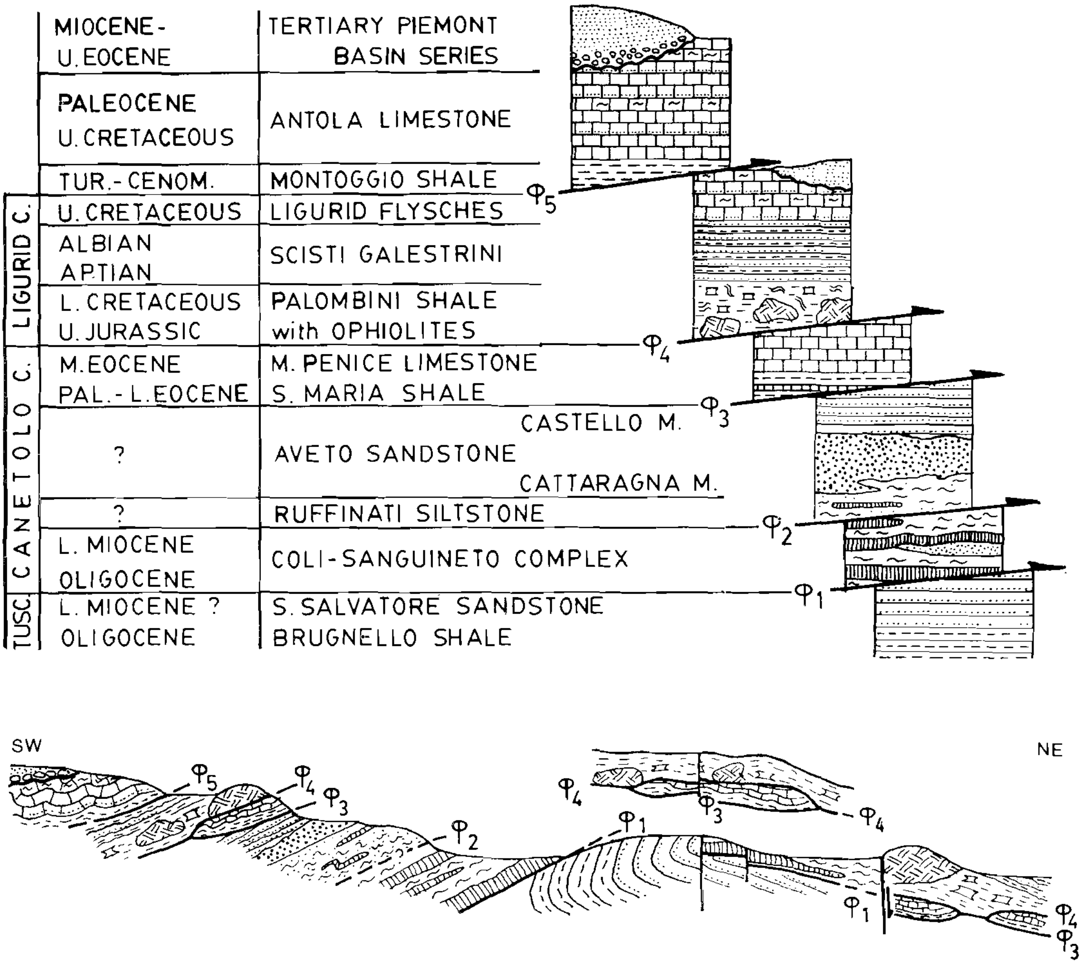


fig. 9 Top: columnar section of the units described in this section.
Bottom: cross-section through the window of Bobbio showing the tectonic superposition. For legend: see figure on top. Figures are not to scale.

- The Ligurid Complex.

The window of Bobbio is bordered by outcrops of the Ligurid Complex. Ophiolites are always present in the basal part of the complex and thus mark the limit of the window. In the last decades various attempts have been made to split up the Ligurids into sub-units (Elter and Raggi, 1965; Barbieri, Papani and

Zanzucchi, 1968; Abbate and Sagri, 1970; Decandia and Elter, 1972; Pagani et al., 1972; Braga et al., 1973). These attempts did not lead to unanimity, yet a rough subdivision in internal and external Ligurid sub-units has been accepted, however. The Ligurid sub-units may be conformably or unconformably overlain by semi-allochthonous deposits.

- The Antola sequence.
  Formerly, the Antola sequence was included in the Ligurid Complex. For tectonic reasons discussed in section IV we distinguish it from the Ligurids. It is named after the Antola Limestone, an Upper Cretaceous Helminthoid flysch. The sequence is unconformably overlain by the Tertiary Piemont Basin series.
- The Tertiary Piemont Basin series includes molassic deposits ranging in age from Late Eocene to Late Miocene. The conglomerates, concentrated near the base of the sequence, are well known (Borbera-, Savignone Conglomerates). The "Tongriano" of Sacco (1889) is a part of the Tertiary Piemont Basin series.

The Tuscan sequence

7 Introduction

The Tuscan sequence is the lowermost one in the examined area. It is generally correlated with the non-metamorphic Tuscan sequence which is allochthonous all over the Northern Apennines, and is known as the "Tuscan nappe" (Abbate and Sagri, 1970). In the window of Bobbio we deal with the most northwestern outcrop of Tuscan units. Subsurface data are not available, so a definite choice between allochthony or autochthony of the Trebbia outcrops cannot be made. In accordance with the allochthonous position of the Tuscan sequence elsewhere in the

Northern Apennines, the outcrops in the Trebbia valley should be considered allochthonous as well, until autochthony is demonstrated.

The Tuscan sequence comprises two formations here:

2) San Salvatore Sandstone,

1) Brugnello Shale.

8 Brugnello Shale

Ludwig (1929)	Tongesteins-Horizont p.p.; Macigno-Horizont p.p.
Labesse (1963)	Unité de Bobbio, argiles pélitiques
Labesse and Magné (1963)	Macigno, terme inférieur
Mutti (1964)	Macigno, membro inferiore
Bellinzona et al. (1968)	Formazione di Bobbio: Argilliti di Brugnello
Schlüter (1968)	Mergel von Brugnello
Plesi (1974)	Argilliti di Brugnello

The formation is almost continuously exposed between km 86.1 and 86.7 of S.S. 45, north of Marsaglia.
In this section the beds are overturned and they dip towards the SW. The formation is named after the village of Brugnello, located on the left bank of the Trebbia river, 1 km N of Marsaglia.

Lithology

A monotonous sequence of prevailingly silty mudstones with minor sandstone intercalations. Both mudstones and sandstones may be slightly calcareous.
The silty mudstones make up most of the Brugnello Shale. They are often characteristically laminated, which is caused by alternations of muddier (darker) and siltier (brighter) laminae (NQ $306^{3}527^{0}$). Their over-all colour is dark grey.
The lowermost 80 m of the section bear no sandstone beds;

above this level sandstone beds appear but they do not exceed 20 % of the bulk of the formation.
The sandstones are mainly greywackes of the turbidite type. Their grain size ranges in the fine and medium fraction. Bed thickness varies from 5 to 15 cm.
Some cleaner sandstones occur. They lack muscovite and show no gradation.
Incidentally brownish to reddish weathered calcarenites are present. At locality NQ $301^{6}525^{5}$ such a bed of 50 cm thickness can be traced over 40 m. The fresh rock colour is dark grey and it is medium-grained.
A similar rock has been found in the Fosso di Sorina bed (NQ $299^{0}529^{5}$), and in the slump exposed along S.S. 45 at approximately km 86.4. The slump thickness is 10 m. The matrix is silty mudstone.
A shallow channel has been observed on the crest running from Marsaglia to Metteglia (NQ $308^{8}512^{3}$).

The thickness of the Brugnello Shale is at least 700 m.

No stratigraphic transition to underlying formations is known; the lower contact is tectonic everywhere.
The transition to the overlying San Salvatore Sandstone is formed by a rapid increase in both bulk and grain size of the sandstones.

9 San Salvatore Sandstone

Ludwig (1929)	Macigno-Horizont
Boni (1961)	Macigno di Bobbio
Labesse (1963)	Unité de Bobbio, Grès
Labesse and Magné (1963)	Macigno, terme supérieur
Schlüter (1968)	Sandsteine von Bobbio (Cervarola-Sandstein)
Bellinzona et al. (1968)	Formazione di Bobbio: Arenarie di San Salvatore
Dallan Nardi and Nardi (1972)	Arenarie di Monte Cervarola.

A beautiful section is situated between km 89.1 and 90 along S.S. 45. Here the dip gradually decreases from vertical to 40^{o} NE. The formation is named after the village of San Salvatore, located on the right bank of Trebbia at km 90.2 of S.S. 45.

Lithology

The type section includes seven megarhythms of sandstones, silty marls and shales. Both positive and negative gradation occurs.
The sandstones are greywackes. Grain size ranges up to micro-conglomeratic. Conspicuous load-, flute- and groove casts indicate a normal bed attitude. The transport direction is from NW to SE. Bed thickness is up to several meters.
The thickness of the formation cannot be established because of the San Salvatore Fault which cuts the formation parellel to the strike and because of the lack of marker levels. However, minimum thickness is 850 m.
In some localities isolated sandstone pebbles have been found in silty intervals (section near Castello Magrini, hilltop 378 SW of San Salvatore). These pebbles are of intraformational origin.
The transition to the underlying Brugnello Shale is stratigraphic.
The upper boundary is a thrust plane. This has been confirmed by Plesi (1974) and Mutti et al. (1975). In former publications (Labesse, 1963; Bellinzona et al., 1968) the transition was considered to be stratigraphical. According to these authors, the San Salvatore Sandstone grades into the overlying formation (our Coli-Sanguineto Complex) by the so-called "Peli Argillites".
In our opinion the "Peli Argillites" are a tectonic melange of formations that occur along the thrust plane between San Salvatore Sandstone and the Coli-Sanguineto Complex (section 13).
Sedimentological aspects of the San Salvatore Sandstone have been profoundly discussed by Mutti and Ghibaudo (1972).

10 The age of the Brugnello Shale and of the San Salvatore Sandstone

Labesse and Magné (1963) attributed all Tuscan outcrops in the window of Bobbio to the Oligocene. In the Brugnello Shale they found "... une microfaune caractéristique bien que mal conservée et difficilement conservable". The San Salvatore Sandstone (terme supérieur) yielded a fauna of Oligocene age as well, but it is, again, called badly preserved (appendix, 1).

Bellinzona et al. (1968) confer a Langhian age to the sequence, based on correlation of the San Salvatore Sandstone with the Aveto Sandstone; a Langhian age is attributed to the latter on behalf of fossil finds in a conglomerate pebble. We consider this correlation highly hazardous.

Mutti et al. (1975) attributed an Early Miocene age to the entire sequence. He based this age on planktonic foraminifera listed on an inclosure to cited publication. We shall discuss this point in section 28.

Boni et al. (1968) report the occurrence of Langhian microfauna in the Brugnello Shale near Monte Zuccharo. We suspect that sampling has been executed in the Coli-Sanguineto Complex (section 12 and appendix, 2).

Sampling carried out on behalf of the present report supplied no useful faunas. The planktonic foraminifera that were isolated were badly preserved. Neither was nannoplankton found in the samples.

The Canetolo Complex

11 The Coli-Sanguineto Complex

The Coli-Sanguineto Complex crops out on both sides of the Trebbia valley between Confiente (S.S. 45, km 84) and Barberino (km 99.5). The outcrops are separated by the Tuscan sequence in a northern and a southern area.

Formerly the rocks in those two areas were not correlated (Bellinzona et al., 1968; Carta Geologica d'Italia, F 71, 1969). The northern outcrops were called "Complesso di Coli" and the southern ones "Complesso di Sanguineto". In our opinion these two complexes are very similar and we agree with Plesi (1974) who combines them in one stratigraphic unit.

As the Coli-Sanguineto Complex (abbreviated CSC) has greatly been afflicted by tectonics, no definite stratigraphic succession can be established. There is, however, a clear division in two lithotypes:

- a bedded marly facies with sandstones,
- a chaotic shaly facies with limestone blocks.

These facies occur in both northern and southern areas and can be studied in excellent outcrops, resp. along the road from P. Martino to Coli near C. Bracciocarella (NQ $315^{0}548^{7}$) and along S.S. 586 between km 1 and 3.

11^{a} The sandy-marly facies of the Coli-Sanguineto Complex

Ludwig (1929)	Tongesteins-Horizont
Labesse and Magné (1963)	"argile" de Bobbio p.p.
Mutti (1964)	"argilla" di Peli
	"argilla" and "calcare e argilla" della zona Marsaglia-Confiente p.p.
Schlüter (1968)	Hangend-Mergel p.p.
	Kalk-Ton Serie p.p.
	Aveto Sandstein p.p.
	Serie von Metteglia
Bellinzona et al. (1968)	Complesso di Coli p.p.
	Complesso di Sanguineto p.p.
Plesi (1974)	Sotto-unità di Coli-Sanguineto

Lithology

The sandy-marly facies of the CSC includes predominant silty marls with occasional lenses of sandstone.

The marlstones are homogenous, middle grey when fresh, yellowish when weathered. They frequently contain limonite concretions. Some mica and quartz grains are also present.

Intraformational slumps are common.

W of Brugnoni a small conglomerate nest has been observed (NQ $290^{3}592^{7}$). Its pebbles are well rounded and their sizes range from 0.5 to 20 cm. The components are: quartz, phyllite, weathered granitic rock, quartzitic sandstone. Similar pebbles have been found in the small Rio Rocca window at M. Aserei, E of Ciregna. They remind of the Aveto conglomerates by their composition.

The scattered outcrops of sandstone in the marls contain different types of sandstone beds: greywackes, calcareous sandstones and clean quartz sandstones. The latter tend to be homogenous, well sorted and fine-grained. The former types are turbidites.

A special type of sandstone is the type found on the northern slope of M. Zuccharo and, in small outcrop, along the path from Brugnello to I Ronchi (NQ $295^{5}530^{5}$). Both occurrences are situated within the southern area. It is weathered into characteristically reddish and greenish colours, the bedding planes are irregular and bed thickness varies 3 to 30 cm. Flute casts and occasional helminthoids are present. It is interbedded with shales or marls. The intervals grade into overlying homogenous marls.

In the northern area a possible equivalent is exposed on the northern slope of the Carlone torrent valley (NQ $293^{8}556^{6}$).

Another type of sandstone consists of evenly bedded medium-grained beds which lack sole marks. It weathers more profoundly than the other sandstones and, as such, is deep rusty brown. Bed thickness does not exceed 15 cm and beds have been observed to taper out in about 10 m. These beds are marked by two sets of joints perpendicular to the bedding plane. Though a tectonic feature, this joint pattern seems to depend on the homogeneity of the rock and is a useful feature for recognition in the field.

11^{b} The shaly facies of the Coli-Sanguineto Complex (olistostromes)

Ludwig (1929)	Kalk-Ton-Horizont
Labesse and Magné (1963)	"argile" de Bobbio p.p.
Schlüter (1968)	Olisthostrome der Kalk-Ton-Serie
	Kalk-Ton-Serie
Bellinzona et al. (1968)	Complesso di Coli p.p.
	Complesso di Sanguineto p.p.

The shaly facies of the CSC comprises a chaotic mixture of dark brown and black shales with disrupted beds and blocks of white micritic limestone, bluish grey limestone, micaceous sandstone and calcarenite. In a fresh exposure the shales have a scaly appearance and no visible bedding.

Levels of the shaly facies of the CSC alternate irregularly with the sandy-marly facies and the thickness of the levels varies from several hundreds of meters to a few meters. The contact between the two lithologies may be abrupt or transitional. Particularly abrupt contacts have been observed along the road P. Martino-Coli at approximately km 5.5 and at locality NQ $322^{0}545^{6}$). A transitional contact is well exposed along S.S. 586 near Sanguineto (km 2.2). The passage from the sandy-marly facies to the shaly facies occupies an interval of about 30 m here.

The shaly facies is generally interpreted as an olistostromes deposit.

The shale matrix, the micrite limestone, the bluish grey limestone and the calcarenite obviously originate from the Monte Penice sequence. Labesse (1963) identified fragments of the Ligurid calpionellid limestone as well.
The olistostrome on the right bank of the Rio Rondinera (the Marsaglia olistostrome at figs. 22 and 23) differs from the other ones in the CSC. This olistostrome contains chondrite-bearing sandstone which reminds of the Aveto Sandstone. It also contains bioturbated sandstone intercalated with equally bioturbated siltstone. Both are strongly bleached. They yield no microfauna and they are not known to occur elsewhere in Ligurid or Subligurid sequences.

12 The age of the Coli-Sanguineto Complex

- The sandy-marly facies

Several authors have reported findings of microfauna: Pannella and Pizzocchero (1962) sampled near Peli-Averardi and near Brugnoni (Rio Assalto). The samples were dated as Late Oligocene-Aquitanian (appendix, 3).
According to Labesse and Magné (1963) the "argile" de Bobbio", which corresponds to our sandy-marly facies of the CSC, yields fauna of "undoubtedly Oligocene age at all levels of the formation" (appendix, 4). This age refers only to the northern outcrop area.
Mutti (1963) collected samples in the "argilla" lens near Bernazzani and along the Rio Rondinera. M.B. Cita dated them as Early Oligocene (appendix, 5).
Later Mutti (1964) added more data. A Middle Eocene microfauna was reported from the "argilla" lens at the bifurcation of S.S. 45 (appendix, 5). This result contradicts our datation of the same lens to the Oligocene-Miocene boundary (appendix, 8; sample c). On the right bank of the T. Curiasca near Peli a

possible Late Oligocene-Early Miocene age was established by Mutti (appendix, 7).

The legend of the geological map at 1 : 50.000 by Bellinzona et al. (1968) mentions "Langhiano ?" for the Complesso di Coli and "Miocene pre-langhiano" for the Complesso di Sanguineto. These ages probably arise from the supposition that the Formazione di Bobbio (Tuscan sequence) is of Langhian age and that it is stratigraphically interposed between the Coli and Sanguineto Complexes (fig. 5).

Boni et al. (1968) report a Miocene (Langhian) microfauna from silty marls of the Brugnello Shale near point 961 on the topographic map (NQ $334^{7}503^{3}$) (appendix, 2). We suppose that the samples have been taken in the Coli-Sanguineto Complex instead of the Brugnello Shale (fig. 27 and section 27).

Of the many samples we took, only six contained a microfauna which served well enough for age determinations (appendix, 8). They all yielded an Oligocene to Aquitanian age.

- The shaly facies.

  We dispose of age data by Labesse and Magné (1963). Blocks of limestone and sandstone were found to enclose a Lutetian microfauna identical to that of the Monte Penice Limestone and other components contained calpionellid limestone indicating a provenance from Upper Jurassic or Lower Cretaceous Ligurid units. A Lutetian age was also established by the authors in three more samples (appendix, 9).

13 The "Peli Argillites"

Ludwig (1929) distinguished no special rock type near Peli. In the Peli area he mapped a Macigno-Horizont, a Tongesteins-Horizont and a Kalk-Ton-Horizont, roughly matching our San Salvatore Sandstone as well as both facies of the Coli-Sanguineto Complex.

Boni (1961) first mentioned the "argilla" di Peli in informal terms. He described no specific rock type, however. In subsequent publications "Peli Argillites" is used as a formation name, indicating an argillaceous, more or less chaotic sequence of highly variable thickness. It stratigraphically overlies the Tuscan sandstone and it underlies the "Complesso di Coli" with a contact of uncertain nature (Bellinzona et al., 1968). On the geological maps it is figured only N of the San Salvatore Fault.

In order to illustrate the lateral variability of the "argillites" we shall describe some outcrops:

- SE of Bobbio: Strongly deformed Tuscan Sandstone is overlain by 5-10 m of greenish grey marls, and dark brown shales, both chaotic and crushed.
- Near P. Martino, opposite the thermal baths, yellowish marls overlie overturned Tuscan sandstone. The marls show no bedding. Sporadic streaks of dark shale are intercalated. The thickness exceeds 10 m.
- At km 3 of the road P. Martino-Coli, about 10 m of intermixed marls, black shale and limestone fragments overlie, again overturned, Tuscan sandstone.
- N of the Curiasca bridge situated S of Coli, an interval of 30 m thickness of dark shales with deformed limestone blocks overlies normally bedded, undeformed Tuscan sandstones.
- E of Castello Magrini sheared blocks of coarse sandstone and limestone are incorporated in fully intermixed yellowish marls and dark shale (fig. 18). A thin level of marls mixed with subordinate amounts of dark shale persists to the E.
- Along the mule path from M. Tiolo to the T. Curiasca di San Michele more than 100 m of deformed silty marls and sandstones are exposed. The bedding is well preserved but also sheared block of apparently Tuscan sandstone have been observed. This section is obviously different from the others.

We feel that the M. Tiolo sequence reminds of the Brugnello Shale in the outcrops at summit 926 (NQ $329^{2}503^{2}$) on the Costa del Castagno and near Rio dei Frati and we consider the outcrops at M. Tiolo as a tectonic horse clenched in the Coli-Sanguineto thrust plane. The other outcrops are, in our opinion, merely a tectonic mixture of CSC and Tuscan elements. This interpretation solves the problem of the sudden eastward increase in thickness of the "Peli Argillites" and that of the underlying Tuscan sequence, being overturned in many places.
It also abolishes the "Peli Argillites" as a stratigraphic entity.

14 The Ruffinati Siltstone

Boni (1961)	"argilla" di Ruffinati
Maxwell (1963)	Formazione Val d'Aveto p.p.
Elter et al. (1964)	Formazione di Salsominore
Bellinzona et al. (1968)	Argilliti di Ruffinati
Schlüter (1968)	Graumergel-Serie

The formation is exposed along S.S. 586 between km 4 and 12.9. Although this section trends roughly parallel to the strike of the beds, a good impression of the lithology is obtained here. The unpaved road to Brugneto, which branches off at km 10 of S.S. 586 intersects the strike perpendicularly and exposes another good section.
The rocks of the Ruffinati Siltstone are always tectonically deformed. The bedding is right side up.
The formation is named after the Ruffinati torrent, an affluent of the Aveto river.

Lithology

The Ruffinati Siltstone is composed of an alternation of siltstone, sandy siltstone and sandstone. Olistostromes of the same composition as those of the CSC are intercalated.

The siltstone and sandy siltstone are indistinctly bedded. They show no gradation or sole marks. Occasional lamination indicates the bedding. They may be slightly calcareous (S.S. 586, km 11 - 11.7 and 12 - 12.35). The sandstone is mostly turbiditic and fine- or medium-grained and it is slightly calcareous. Bed thickness is usually 5 - 15 cm but may be considerably larger in the upper part of the formation. Pebbly lag deposits are sometimes present in the turbidites e.g. at km 81 - 82 of S.S. 45. At km 6 of S.S. 586 a slump level of 8 m is intercalated in a sandstone-siltstone intercalation.
Thin-bedded sandstone-shale intercalations occurs especially near the top of the formation. The sandstone is turbiditic, micaceous, and its colour is grey when fresh and pale greenish when weathered. Bed thickness is 5 - 50 cm. Conspicuous joints are often developed, perpendicularly to the bedding planes.
In the incision of S.S. 586 (km 12.83 - 12.87) massive sandstone beds reach a thickness of 8 m. With the exception of sole marks no sedimentary structures have been observed.

Olistostromes

Discontinuous levels of olistostromes are present. The olistostromes are lithologically similar to the shaly facies of the CSC but the quantity is much smaller in the Ruffinati Siltstone.

Relationships with adjacent formations

The Ruffinati Siltstone is separated from the CSC by a disputed contact. Elter et al. (1964) include it in the Coli-Sanguineto Complex. Mutti (1964) gives a stratigraphic contact; Bellinzona et al. (1968) figure a contact of uncertain nature and Schlüter (1968) reports an intensely folded thrust plane. The course of the contact as claimed by the authors never coincides, for field exposures are scarce and the lithologic differences are small.

The Ruffinati Siltstone underlies the Aveto Sandstone by a disputed contact as well. However, the recent incision of the road Ruffinati-Lisore exposes a gradual stratigraphic transition in spite of much shearing. The section is, upward from below:

- indistinctly bedded silty marls, overlain by an interval with thick-bedded grey graded sandstone beds with incidental shale intercalations.
- A variegated thin-bedded sandstone-shale alternation. The sandstone beds are fine-grained and densely jointed.
- At approximately 150 m above the Aveto bed massive thick-bedded sandstones appear. Greenish beds are alternating with grey ones.
- After 150 m (100 m under Lisore) the first fine-grained conglomerates -or rather pebbly sandstones- appear. The size of the pebbles varies from several cm to a maximum of 10 cm.
- Directly under Lisore the first coarse conglomerates appear as boudins in the thin-bedded sandstone-shale facies. SW of Lisore (NQ $314^{0}426^{5}$) conglomerate lenses are intercalated in the sandstone-shale alternations.

The thickness of the Ruffinati Siltstone is of the order of 400 m. This is only an estimate because of the intensive deformation of the rock.

We have not found a useful fauna in the Ruffinati Siltstone. Schlüter (1968) reports a Late Eocene-Oligocene age (appendix, 10).

15 The Aveto Sandstone

This formation has been discussed by various authors. Roccati (1921) first drew attention to its conglomerates and Rodolico (1941) reported the presence of greenstones and other crystalline rocks in it.

Names such as Aveto Sandstone or Aveto Conglomerate have been current since. (Ten Haaf, 1961; Boni, 1961; Mutti, 1964; Elter et al., 1964; Kube, 1965; Bellinzona et al., 1968; Schlüter, 1968; Elter et al., 1969; Abbate and Sagri, 1970; Plesi, 1975; Aiello, 1975).

The Aveto Sandstone is almost continuously exposed along S.S. 586 in a roughly SW-dipping section with a normal attitude. It is convenient to split up the Aveto Sandstone in two members:

b) Castello Member: a sequence of turbiditic sandstones;

a) Cattaragna Member: conglomerates, green tuffites and subordinate turbiditic sandstone beds resembling those of the Castello Member. Some levels with variegated shales are also present.

15[a] The Cattaragna Member of the Aveto Sandstone

The Cattaragna Member has been named after the village of Cattaragna, situated on the right slope of the Aveto valley, 400 m above the power plant of Ruffinati.

Lithology

The rock types encountered in the Cattaragna Member are:

- greenish to green sandstone,
- polymict conglomerate,
- variegated shale,
- turbiditic sandstone,
- grey shale.

The road incision of S.S. 586 exposes the following section, starting from km 13.1:

30 m of red or green shale interbedded with thin beds of dark grey calcarenite and bright grey micritic limestone; both are siliceous. The micrite bears fern-like fossils. Elsewhere at

the base of the formation, variegated shale has not been found. After 10 m of strongly deformed calcareous sandstone and greenish grey shale the sandstone becomes coarser. Microconglomeratic lag deposits appear and after 40 m the first pebbles have been observed in a coarse matrix.
From this point on, conglomerates and medium- or coarse-grained greenish grey sandstone are interbedded with turbiditic sandstone and grey shale. The turbiditic sandstone is similar to that of the overlying Castello Member. Paleocurrent directions are from SW to SE.
After the passage of another interval with squeezed red and green shale at km 15.5 bright green sandstone appears, associated with thick conglomerate beds.
The green sandstone is composed of redeposited volcanic debris of andesitic composition (Elter et al., 1969; Aiello, 1975, see appendix, 12) and is to be classified as a tuffite.
The conglomerates have irregular, sharp basal surfaces. One conglomerate intercalation is composed of one or more graded units. Both positive and reversed grading occur. The conglomerate pebbles are sub-rounded or well rounded. Their sizes amount to 1 m. They often lie embedded in a sandy matrix. We have found pebbles of green tuffite in the conglomerate.

The composition of the conglomerates is, according to Aiello (1975):
50 % gneiss and micaschist,
15 % granite,
10 % quartzite,
15 % marly limestone, shale, sandstone, lava,
10 % chert and other rock types.

Different proportions are reported by Kube (1965) from a sampling site N of Castello:
60 % ophiolite,

35 % metamorphic and crystalline rock,

5 % sedimentary rock.

Schlüter (1968) reports from Casale:

26 % metamorphic rock,

26 % magmatic rock,

48 % sedimentary rock.

Apparently, ample variations exist in the composition of the conglomerates. Indeed, Schlüter reports an upward increase in basic rocks and a decrease in sedimentary components.

The thickness of the conglomerate body is highly variable. Near Casale and on the crest N of the Rio di Carpegna conglomerate blocks are scattered over the valley slope. We have found no reliable outcrops of conglomerates here. Further to the S, on the Ronco Marcon, the thickness exceeds 1000 m, but according to Kube and to Elter et al. (1969) the stratigraphic sequence has been cut by reverse faults, so this thickness is apparent and probably exaggerated.

No reliable age data exist of the Cattaragna Member. A Langhian age has been inferred on account of the faunal content of thin sections of conglomerate pebbles of marly limestone by Boni et al. (1968) (appendix, 13). Maxwell (1963) and Kube (1964) have reported and Eocene age. As reworking of Eocene rocks has very frequently occurred in the Northern Apennines these datations only indicate a maximum age.

Most age estimates are based on lithologic correlation with volcanoclastic rocks of mainly andesitic composition. These rocks frequently occur in Oligocene and Aquitanian sequences in the Western Mediterranean area. (Aiello, 1975) (see also section 21).

15^b The Castello Member of the Aveto Sandstone

The Castello Member is named after a small village near the Boschi bifurcation of S.S. 586. A good exposure is to be found here.

The member crops out in the Aveto valley SW of S.S. 586, km 20 and in the small Traschio window situated N of Ottone.

Lithology

The Castello Member is composed of a monotonous alternation of turbiditic sandstone and shale with occasional calcarenite intercalations. The sandstone is a greywacke and resembles the sporadic non-tuffitic sandstone beds in the Cattaragna Member. Chrondrites often occur in the Castello Member.

The transition from the Cattaragna Member to the overlying Castello Member is gradual. With the reduction of the green tuffites and the conglomerates the valley widens and becomes less steep.

There are no direct age data of this member. Near the bridge over the Rio Remorano a single bright limestone bed has been found to contain foraminifera. The fauna is not preserved well enough for determination.

16 The Monte Penice sequence

The Oligo-Miocene of the window of Bobbio is overlain by a ragged thrust sheet consisting of Paleogene shales and limestones. Two formations are distinguished by Bellinzona et al. (1968):

b) Monte Penice Limestone: an alternation of calcarenites, micrites, marly limestones, marls and subordinate shales,

a) Santa Maria Shale: dark shales interbedded with occasional thin beds of micritic limestones and calcarenites.

16^a Santa Maria Shale

Formerly the shale has been included in the Kalk-Ton-Horizont (Ludwig, 1929). The Italian translation "calcare e argilla" is still used to indicate outcrops of contorted shales and limestone. The name refers to a lithology rather than to a formation, which is perfectly understandable as it is almost impossible to distinguish "calcare e argila" underlying the Monte Penice Limestone (= Santa Maria Shale) from the olistostromes of the same material in the CSC and in the Ruffinati Siltstone or from landslide deposits. Commonly the stratigraphic position is decisive.

The Santa Maria Shale is always strongly deformed due to its tectonic situation along the M. Penice thrust plane. It is well exposed along the unpaved road from Bobbio to the village of Moglia on the right bank of the Carlone torrent.

Lithology

The shales are dark rusty brown or black and contain no carbonates at all. Occasional pyrite crystals have been observed. There are three main types of limestone beds:

- white micritic limestone in beds with an average thickness of about 10 cm although a few reach 45 cm.
  The micrites are often siliceous, as such they remind the Ligurid Palombino Limestone. Usually, however, the Palombino Limestone is more siliceous and, after weathering, its fragments are more angular.
- dark bluish grey calcarenites occur in beds not exceeding 10 cm of thickness.
- marly limestone beds.

We have not found transitions to the overlying M. Penice Limestone. Neither do we venture into thickness estimates. The formation is badly exposed and highly subject to landslides.

16^b Monte Penice Limestone

The Monte Penice Limestone includes a sequence of various kinds of limestones, marls and sandstones, interbedded with subordinate shale intervals.
Good exposures are situated along the S.S. 461 from Bobbio to the Penice pass along the last km before the pass.

Calcareous turbidites, micritic limestones, micaceous sandstones, marly limestones and marls are common rock types. Microconglomerates and shales also occur.
Incidentally thin levels of variegated shales occur, e.g. on the north slope of M. Aserei (Braga, 1965) and on the southern slope of M. Penice.

The Monte Penice Limestone stratigraphically overlies the Santa Maria Shale. The top is truncated by the Ligurid overthrust. Consequently the thickness is variable: from zero to several tens of meters, e.g. in the Rio Rondinera valley, but it exceeds 500 m in the folded sequence at M. Penice itself (fig. 29).

The age of the Monte Penice Limestone is Lutetian (Labesse and Magné, 1963 (appendix, 11).

17 The Ligurid Complex

We have not studied the stratigraphy of the Ligurid Complex and therefore we shall review only the main stratigraphic units, using their informal names. These units are:

- flysch formations, either arkosic or calcareous. (Upper Cretaceous-Paleocene)
- Scisti Galestrini (Cenomanian-Turonian)
- Palombino Shale (lower Cretaceous)

The Palombino Shale is a complex of dark shales interbedded with light-coloured limestone beds with conchoidal fracture.

The limestone is commonly contorted and fragmented. It is silicified along the bedding planes and forms thus knuckle-bone shaped blocks (= palombini) after selective erosion or dissolution. The shales often enclose blocks and masses of:

- calpionellid limestone (upper Jurassic-lower Cretaceous)
- diasprini (= chert) (Malm)
- ophiolites (upper Jurassic-lower Cretaceous)
- granites, granite breccias with radiometric age 220 - 230 M.y., and attributed to the final stages of the Hercynian cycle.

Strong deformation prevents thickness measurements. Usual thickness is several hundreds of meters (Abbate and Sagri, 1970).

The Scisti Galestrini overlie the Palombino Shale in the examined area. They include the Scabiazza Sandstone: a regular alternation of thin bedded turbiditic sandstones and shales, well exposed in the upper Avagnone valley near Brallo.

In the area near M. Scaparina (el. 1175) situated W of the M. Penice summit, the lithology of the Scisti Galestrini is more heterogenous. Apart from thin bedded turbiditic sandstones there are also intervals with thick beds, that have microconglomeratic lag deposits containing clasts of limestone and metamorphic rock (gneiss, micaschist). Occasional limestone is exposed in the fresh road incision near Cima di Valle Scura. Bed thickness is up to 120 cm here. Contrary to Bellinzona et al. (1968), Labesse (1963) discerned a separate unit in this area: the "Unité du Mont Arpeselle".

Variegated shales overlie the Scisti Galestrini and also occur as patches in the latter. The character of this association cannot be established because of the intense deformation of the rocks.

The Ligurid sequence is usually topped by a flysch, either arkosic (the Gottero Sandstone, that crops out at the Apenninic divide and S of it) or a calcareous Helminthoid flysch (Monte

Cassio Limestone; Monte Caio Flysch).

18 Antola Limestone

We have separated the Antola Limestone from the Ligurid flysches, not on stratigraphic arguments but on tectonic ones (section IV). Like the Ligurid Monte Caio and Monte Cassio flysches, it is a sequence of turbiditic limestones interbedded with marls, shales and sandstones in varying proportions.
The thickness of the formation is 2000 m S of the Apenninic divide but it decreases to the N.
Scholle (1971) reported complete analogy of the Antola Limestone with the flysch of the Franco-Italian Maritime Alps: "... one finds similar paleocurrent directions (from SW to NE), similar petrographic makeup (derivation from a predominantly granitic source with some metamorphic and slight sedimentary cover), similar ages and similar associated sections".

The marly Albirola Formation overlies the Antola Limestone. Its age is Paleocene.

The semi-allochthonous sequences

19 Tertiary Piemont Basin series

Equivalents, in part, are "Tongriano" (Sacco, 1889), and Ranzano-Bismantova sequence p.p. (Sestini, 1970).
It is a predominantly clastic series with local thick conglomerate intercalations, turbiditic sandstones, marls, slumps and olistostromes. The age of the sequence is upper Eocene-Miocene.

The Tertiary Piemont Basin series unconformably overlies the Antola-Albirola sequence. Its most conspicuous feature is the extremely thick conglomerates in the Borbera-Scrivia area.

They swiftly taper out towards N and NE, and in the Staffora valley only small patches of conglomerate remain. In the same direction the conglomerate composition changes from polymict to oligomict: in the Borbera area there are abundant basic rocks from the Voltri-Savona Massif while the conglomerates near Castellaro and C. Bertella are mainly composed of limestone pebbles derived from the Antola Limestone.
For more detailed information, see Van der Heide (1941), Ibbeken (1968), Labesse (1966), Galbiati (1977).

The Tertiary Piemont Basin series continues westward as far as the Langhe region and is limited in the N by the Varzi-Villalvernia lineament, the significance of which will be discussed in section IV.

20 The Ranzano-Bismantova sequence

North of the Varzi-Villalvernia line the Ligurid Complex crops out. It is overlain-generally unconformably- by the Ranzano-Bismantova sequence, a molassic sequence starting in the late Eocene. It continues throughout the Oligocene and Miocene. Recent stratigraphic investigations are reported by Gelati et al. (1974).

21 Remarks on the Canetolo Complex

a) Correlations

In 1970 Abbate and Sagri introduced the name Canetolo Complex to indicate the scattered outcrops of "calcare e argilla" and associated rocks; it is overlain by the Ligurid Complex proper. The concept to this Subligurid Canetolo Complex has been introduced by Elter et al. (1964), who distinguished an allochthonous unit formed by tertiary rocks squeezed in between the external unit of Bobbio-Pracchiola and the internal

Monte Caio Helminthoid Flysch unit.

The lithologic units reported in the Canetolo Complex are (fig. 10):

- Canetolo shales and limestones: an irregular alternation of dark shales and various types of limestones. This lithology is commonly referred to as "calcare e argilla" or Kalk-Ton-Serie (Ludwig, 1929). Age: Paleogene.
- Groppo del Vescovo Member: lenticular intercalations of several types of limestones. Age: Paleocene-M. Eocene.
- Ponte Bratica Member: fine-grained turbiditic sandstones and shales. Age: unknown.
- Petrignacola Member: thick bedded coarse-grained turbiditic sandstones with subordinate intercalations of shale and frequent conglomerate lenses. Age: unknown.

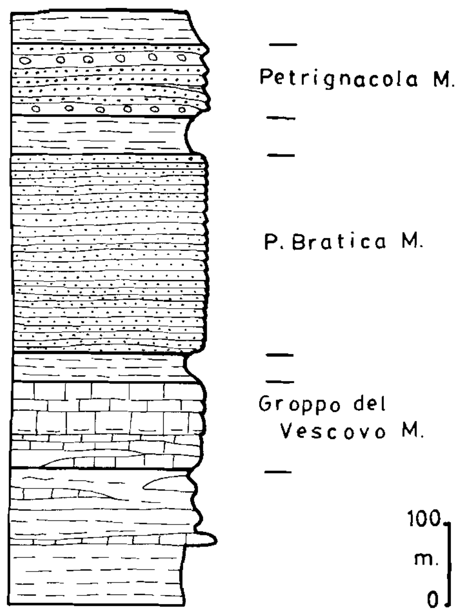


fig. 10 Columnar section of the Canetolo Complex in the Parma valley (Abbate and Sagri, 1970). Portions without letters pertain to the Canetolo shales and limestones.

The units of the Bobbio window have been tentatively correlated with the Canetolo Complex (Abbate and Sagri, 1970; Aiello, 1975; Plesi, 1974):

Canetolo shales and limestones	:	Santa Maria Shale, Coli-Sanguineto Complex,
Groppo del Vescovo Member	:	Monte Penice Limestone,
Ponte Bratica Member	:	Ruffinati Siltstone,
Petrignacola Sandstone	:	Aveto Sandstone.

In accordance with Bellinzona et al. (1968) we split up the Canetolo Shales and limestones in a Paleogene unit underlying the M. Penice Limestone (S. Maria Shale) and an Oligo-Miocene unit with "calcare e argilla"- olistostrome intercalations (Coli-Sanguineto Complex).

Aiello (1975) correlated the Aveto Sandstone with the Petrignacola Sandstone and the Monte Senario Sandstone of the Parmesan and Bolognese Apennines.

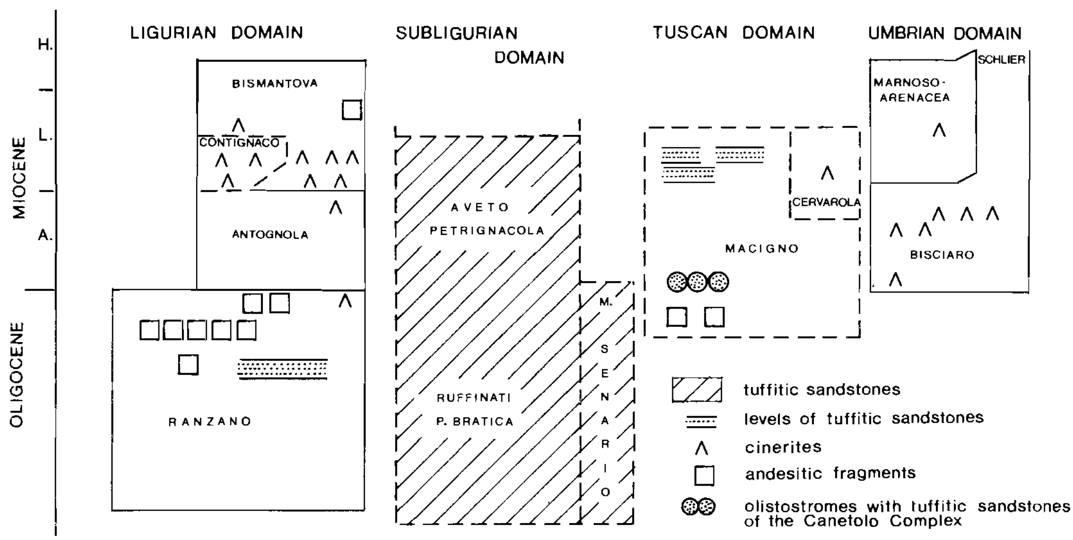


fig. 11 Stratigraphic distribution of the Oligo-Miocene tuffitic sandstones (S.L.) and cinerites in the Northern Apennines. (Modified after Aiello (1975).

Sandstone and conglomerate composition, paleo-current direction, the morphometry of the pebbles and cobbles and the petrography of the sandstone grains suggest a common origin (appendix, 12). In the Petrignacola Sandstone, marly cobbles have been found to contain an Early Miocene microfauna (fig. 11).

Elter et al. (1969) proposed a common origin of the Taveyannaz Sandstone of the French and Swiss Alps and the volcanic sandstones of the Northern Apennines, e.g. the Aveto and Petrignacola Sandstones. This opinion is based upon the occurrence of at least 80 % of andesitic elements in the sandstones and, in the non-volcanic fraction, of epidote-bearing rock debris and glaucophane- or crossite-bearing quartzite. Also, similar biodetritic elements are reported to occur in all localities.

b) The components of the Aveto Sandstone

The components point to several source areas:
The tuffites are considered to have derived from an andesitic belt which is thought to have existed in Oligocene and/or Miocene times. As the beds are turbidites, the clastics may have been transported lengthwise through the Aveto basin from NW to SE. For the conglomerate constituents, this is not possible. The conglomerates have been deposited as olistostromes originating from a nearby area; they must have slided transversely into the Aveto basin. The conglomerate components are granite, metamorphic rocks, sedimentary rocks and ophiolites in varying proportions, implying several provenance areas.

The association of granites and granite braccias with ultrabasic rocks repeatedly occurs in the Ligurid Complex. To explain this association, we assume that relicts of the attenuated Hercynian crust remained on the Tethys Ocean floor after opening of the basin. These sialic relicts, together with ophiolites, have been tectonically emplaced in the lower terms

of the Ligurid sequence.
The Canetolo Complex occupied a far more external position in the basin. Similar relicts of the Hercynian crust or of a Hercynian continental margin may have supplied the granitic and metamorphic rocks to the Aveto conglomerates after they have been raised next to or within the Aveto basin.

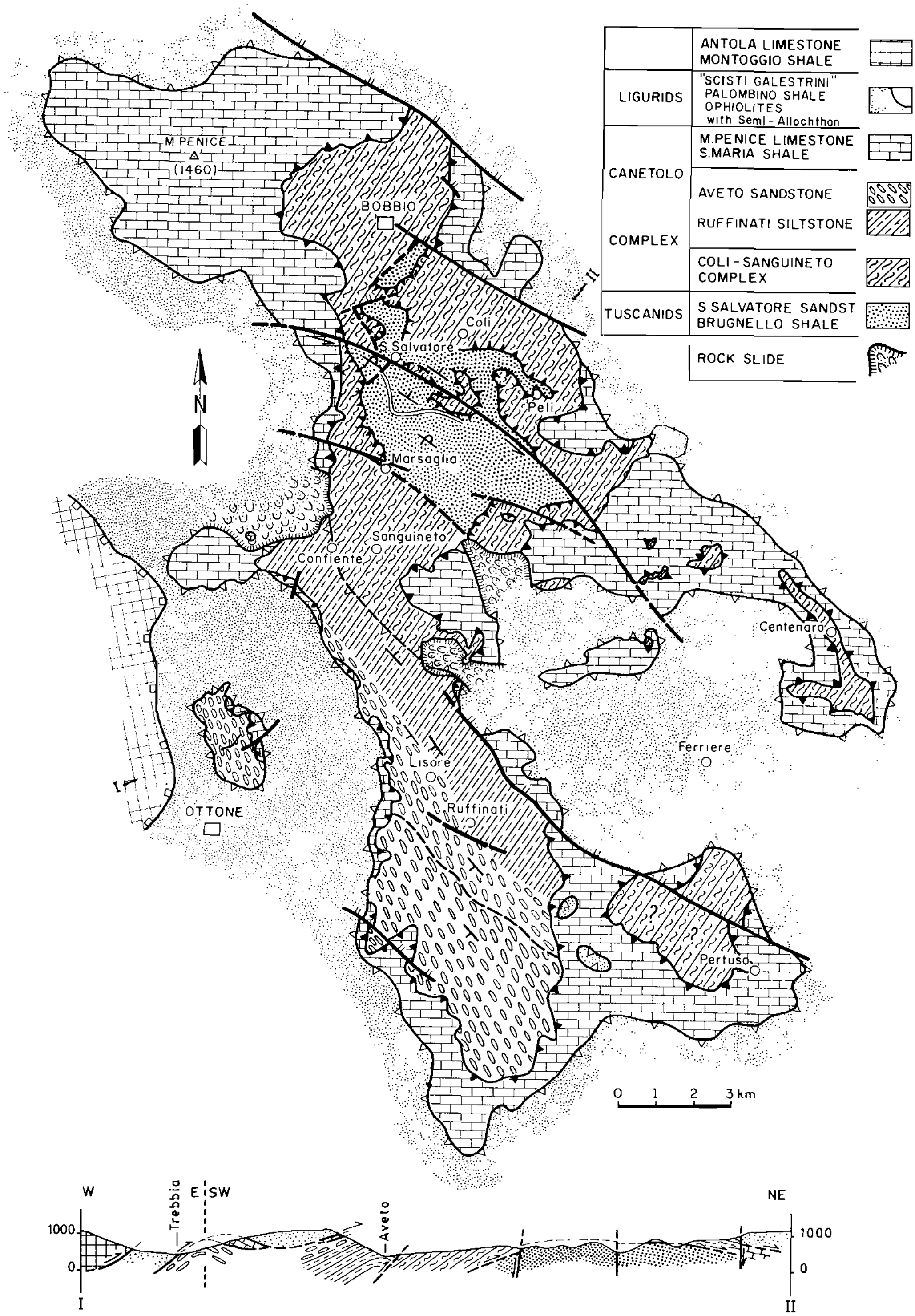


fig. 12 Tectonic map and cross-section of the window of Bobbio.

III TECTONICS

22 Introduction

Three main tectonic units are involved in the geology of the window of Bobbio:

- the Ligurid Complex,
- the Canetolo Complex,
- the Tuscanids.

We follow the main subdivision introduced by Teichmüller (1927), Tillmann (1932) and De Wijkerslooth (1934).

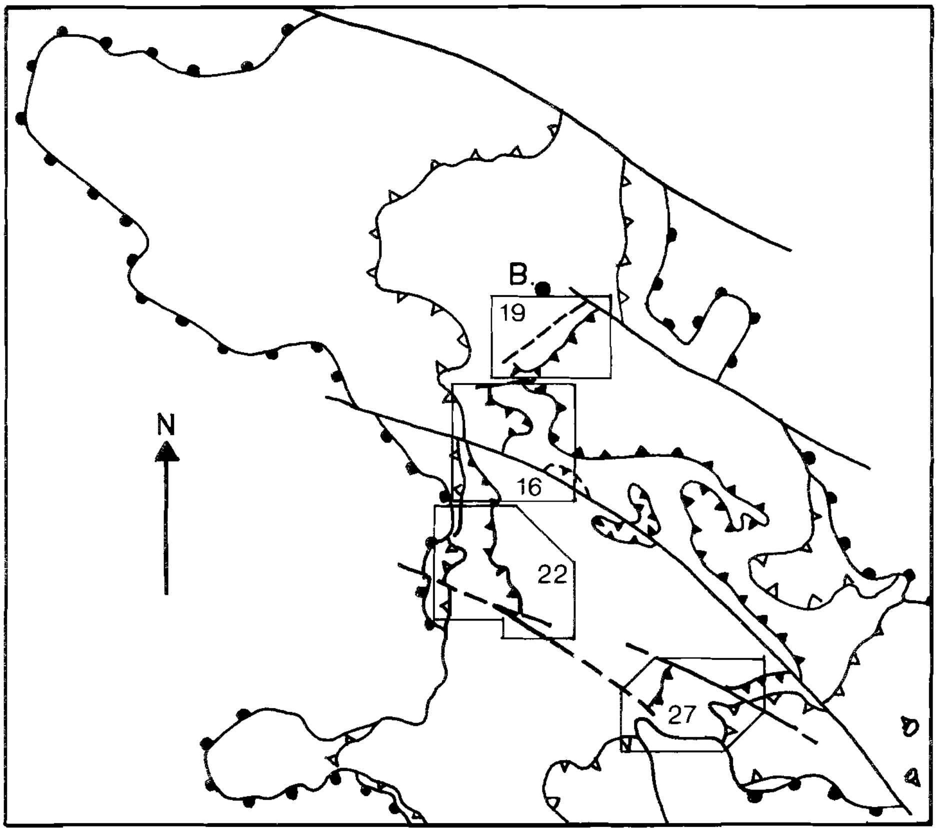


fig. 13 Index map to detailed geological maps. Numbers refer to figures in text.

The Canetolo Complex was added later by Abbate and Sagri (1970). These authors distinguished between the Tuscanids I (a metamorphic sequence, considered autochthonous), and the Tuscanids II, a nappe comprising the non-metamorphic Tuscan sequence. The Ligurids are a set of superimposed complexes of which the Canetolo Complex will be taken as a separate Subligurid unit. It tectonically overlies the Tuscanids II. The Tuscanids I are not exposed in the studied area. Therefore, we shall refer to the Tuscanids II simply as Tuscanids.

23 The Tuscanids

The Tuscan sequence in the window of Bobbio is subdivided by Bellinzona et al. (1968) in:
- San Salvatore Sandstone,
- Brugnello Shale.

The two formations are folded into a large recumbent syncline with an axial plane that dips approximately 15^{o} SW. The southwestern limb, composed of overturned Brugnello Shale and San Salvatore Sandstone, dips at angles up to 60^{o} SW. The northeastern limb is formed out of moderately NE dipping San Salvatore Sandstone.
A fault cuts lengthwise through this syncline and downthrows the northern block. We shall call it the San Salvatore Fault and discuss its offset in section 29.

The competent San Salvatore Sandstone lies in the core of the syncline and is hardly affected by small scale tectonics. More deformation has been observed in the Brugnello Shale. Minor reverse faults occur frequently: they tend to dip towards the SW and their course is wavy in such a way that they fade out parallel to the bedding planes. This causes a scaly appearance of the rocks.
A particularly crushed zone lies along the transition between the

two formations. This zone coincides with the subvertical strata near the axial plane of the recumbent syncline and it may be the result of differential movements between the competent sandstone and the much less competent Brugnello Shale.
In the steeply overturned limb the Brugnello Shale has undergone gentle secondary folding due to gravitation. This phenomenon is observed on the SW face of the Costa della Croce and on the Costa del Castagno, situated NE of Torre Metteglia (fig. 14).

24 The Coli-Sanguineto overthrust

We have already stated that the contact between the Coli-Sanguineto Complex and the Tuscan unit is a tectonic one: the CSC has overthrusted the Tuscan sequence from SW to NE.

fig. 14 Secondary gravitational folding of overturned Brugnello Shale on the Costa del Castagno. Comparable gentle folding at a larger scale has been observed in the San Salvatore Sandstone 300 m W of Costiere (NQ $328^{3}519^{0}$).

Various phenomena accompany the thrust plane (fig. 15):
Along the contact, the San Salvatore Sandstone has been afflicted by shear forces of variable intensity; in some cases no apparent deformation has taken place, in others single sandstone beds have been torn loose and folded. More intense deformation is shown by a footwall-syncline of variable dimensions and in some cases this syncline is heavily distorted.
The Brugnello Shale is deformed in a different way. Crushing of the rock, shearing subparallel to the beds and slicing are the main features here.

We see that the deformation along the northern part of the overthrust contact differs from that along the southern part.

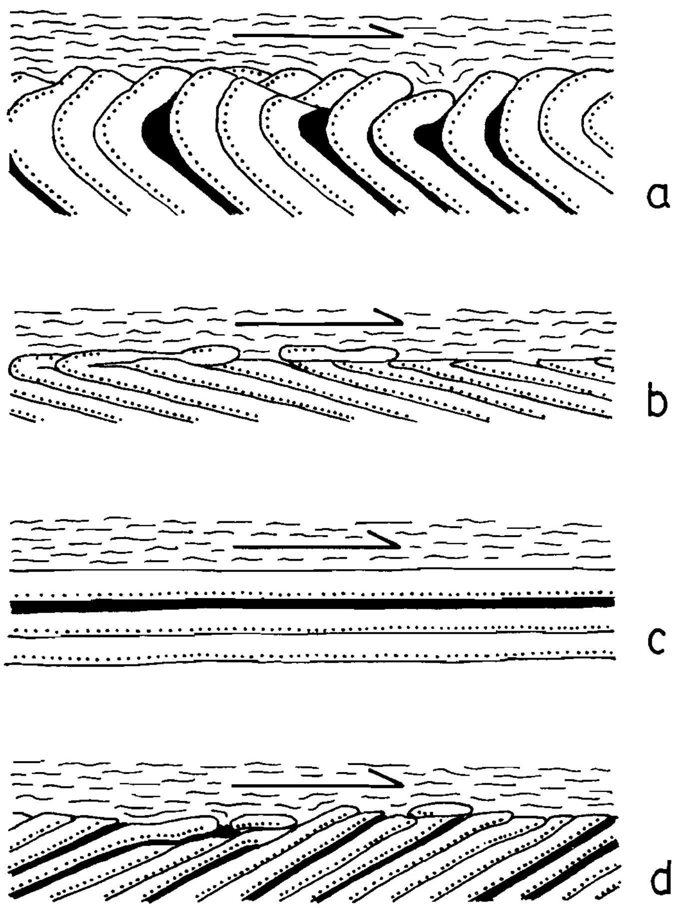


fig. 15 Deformation along the Coli-Sanguineto overthrust at changing attitude of the beds in the footwall.

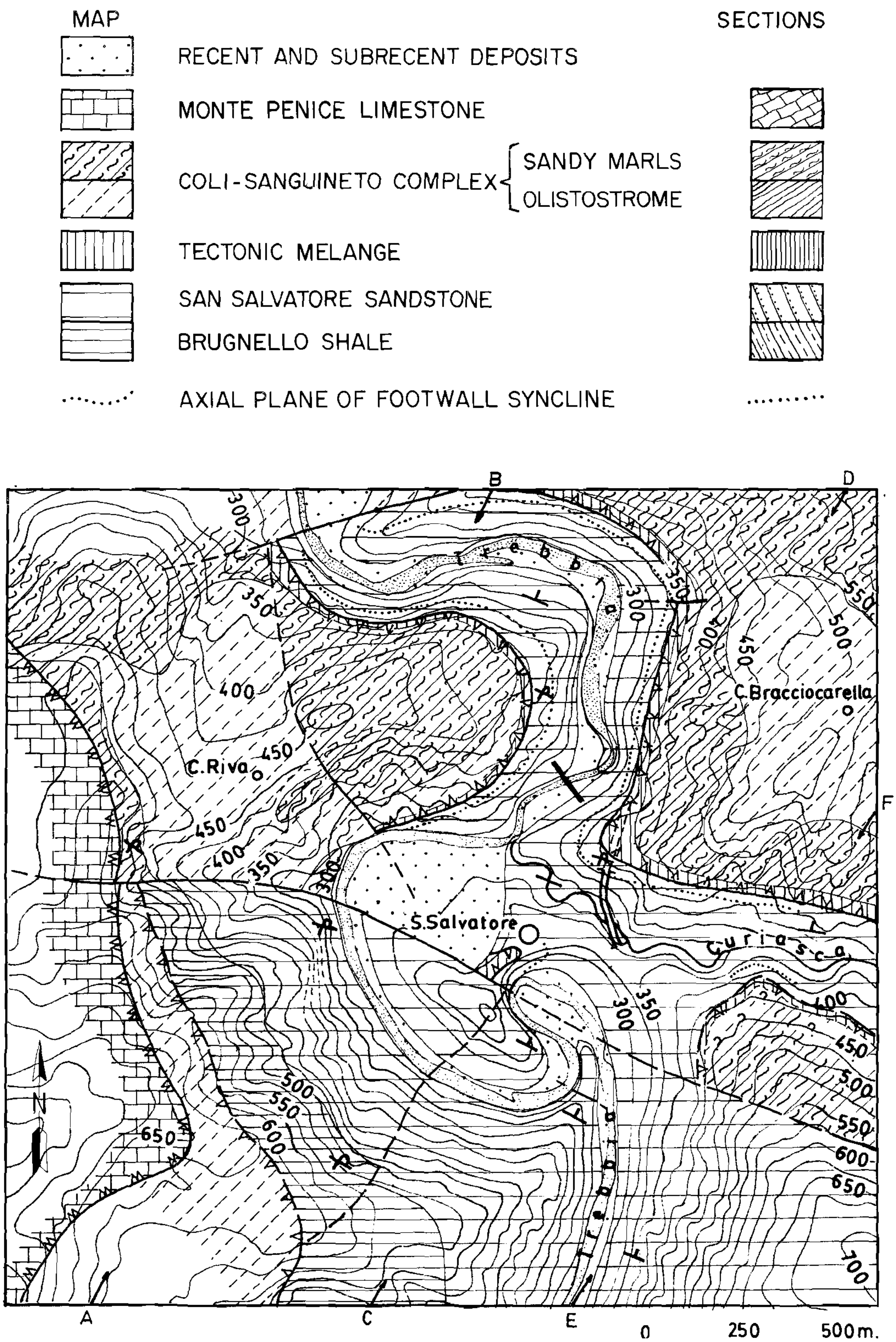


fig. 16[a] Geological map of the Trebbia valley near San Salvatore.

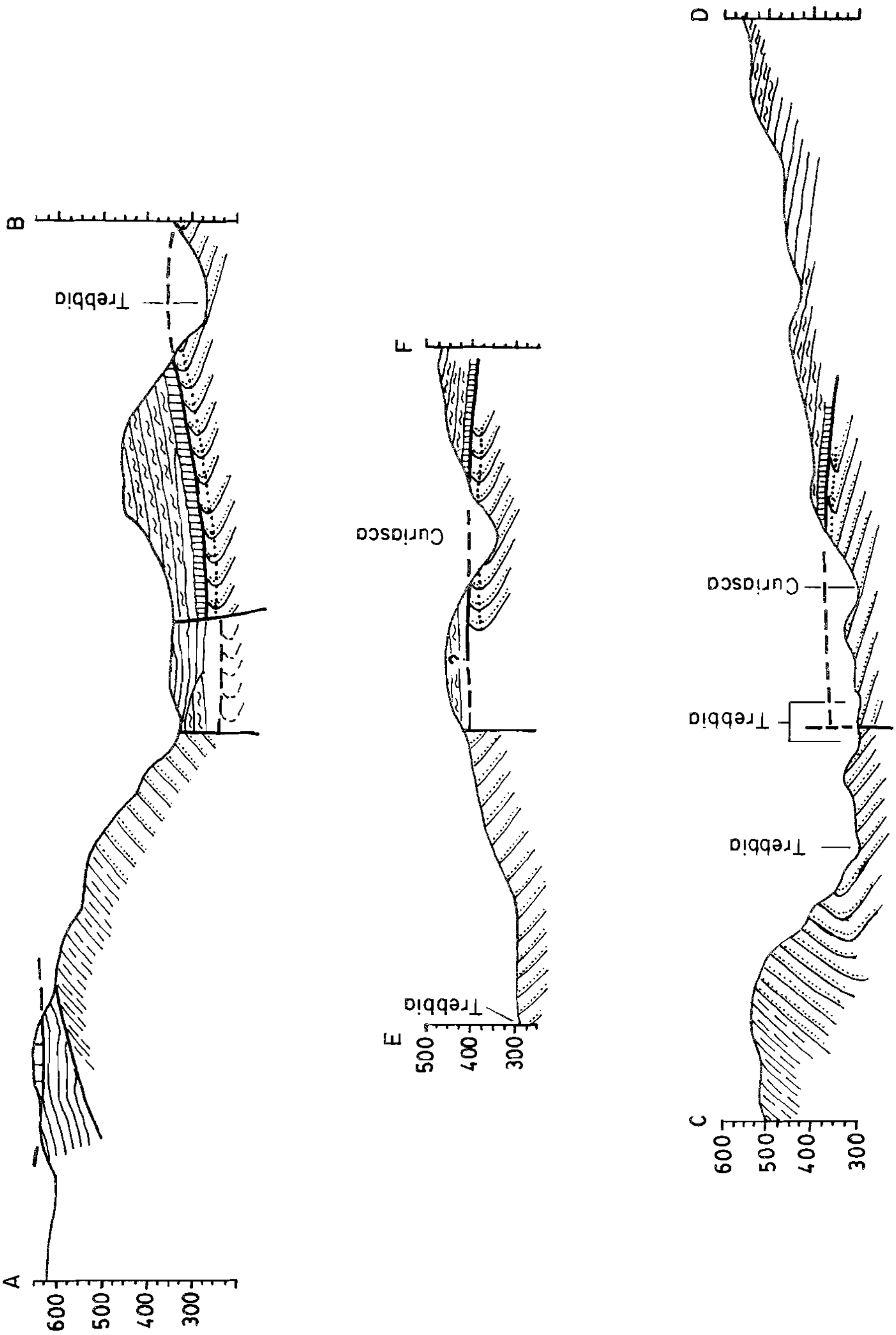


fig. 16[b] Cross-sections to fig. 16[a].

This is due to the varying angular relation between the overthrust direction and the bed attitude in the footwall. Where the thrust plane is parallel to the beds, deformation is minimal (fig. 15^c). If the angle concerned is only slight, then single beds may get peeled off and folded, or attenuated into boudins (fig. 15^b). With increasing angle a footwall syncline may form over a considerable area. Consequently the axial plane of this syncline, which must be considered a drag phenomenon, is roughly parallel to the thrust plane (fig. 15^a).

Along the southern contact, an essentially different situation is presented: here, the overturned beds of the footwall dip against the direction of motion of the thrust, so a footwall syncline is impossible. Instead, there are small reverse faults, movements parallel to the bedding and small-scale occasional folding (fig. 15^d).

Before entering into detailed descriptions of rock deformation at the thrust plane it should be noted that the overthrusting unit (CSC) is an incompetent if not highly incompetent unit. The northern contact is, all along its outcrop, lined by the so-called "Peli Argillites" which are, actually, not a lithostratigraphic unit but a tectonic facies of the Coli-Sanguineto Complex, mixed up with a small amount of rocks that are picked up from the footwall (section 13). Along the southern contact, such a tectonic facies has only been found in the Piano di Robecco area.

25 The footwall syncline

At a large number of localities in the Trebbia valley between San Salvatore and P. Martino, as well as along the lowermost Curiasca valley a footwall syncline is clearly exposed (fig. 16). At all of these localities northeasterly dipping strata have been dragged into an overturned position along the thrust plane. The dimensions of the syncline are up to 200 m near S.S. 45 north of the San Salvatore tunnel (fig. 17) but usually more modest dimensions occur. The dip of the axial plane of the syncline changes from about 10^{o} WSW at its eastern outcrops to horizontal and slightly NE in more eastward exposures. The axial plane remains parallel to the thrust plane. The southwestern limb is always overturned, thus indicating a strong vergence towards the NE.

The small isolated outcrop near and north of Ponte Martino (fig. 19, 20) offers an interesting variation. The sandstone beds are particularly squeezed here and the bedding is obscured by intensive jointing. Detailed measurements of bedding planes, joint planes and occasional cleavages show the presence of a

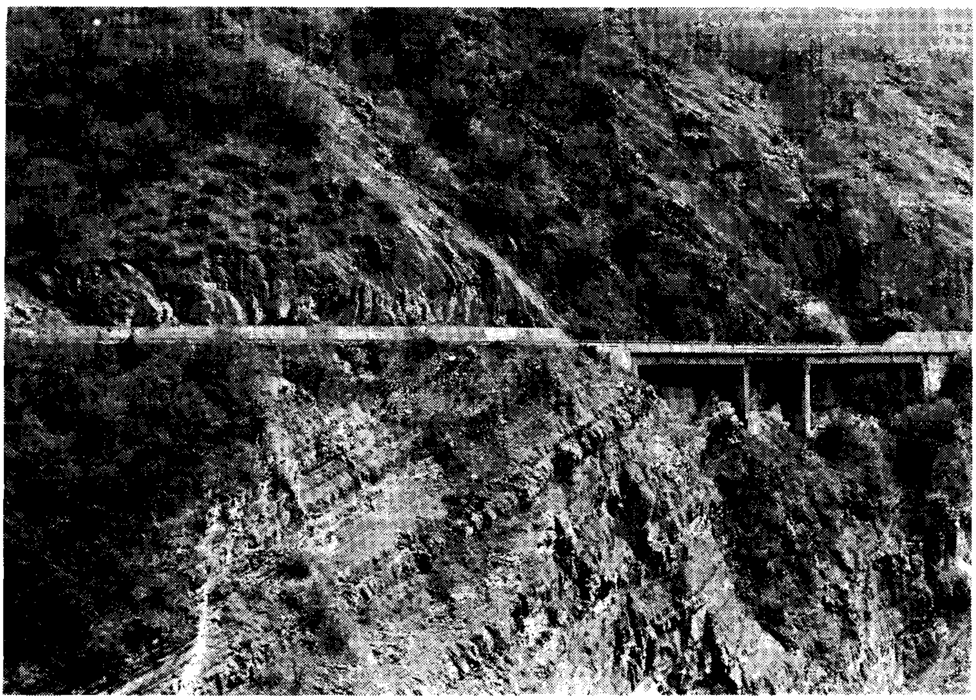


fig. 17 Footwall syncline at the right bank of the Trebbia, N of the tunnel of S.S. 45 at San Salvatore, seen from the left bank.

strongly overturned fold as well. When plotted in a stereogram, a set of A-C joints and possibly and axial plane dipping 10^{o} NW appears (fig. 21).

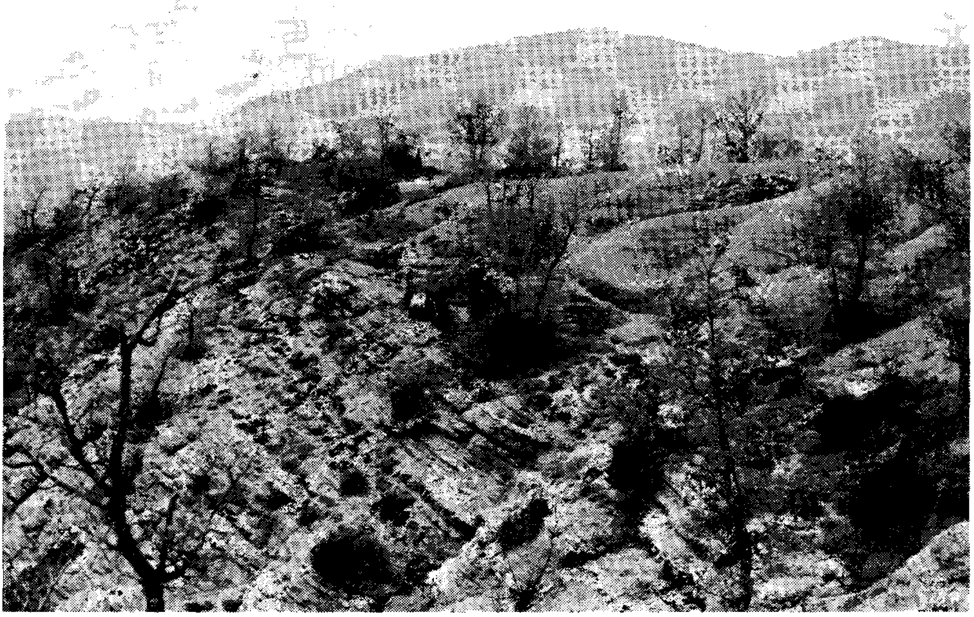


fig. 18 The Coli-Sanguineto thrust plane near Castello Magrini, located on the right bank of the Curiasca torrent. Note the blocks of squeezed sandstone at the contact and the smooth relief of the tectonic melange overlying the contact.

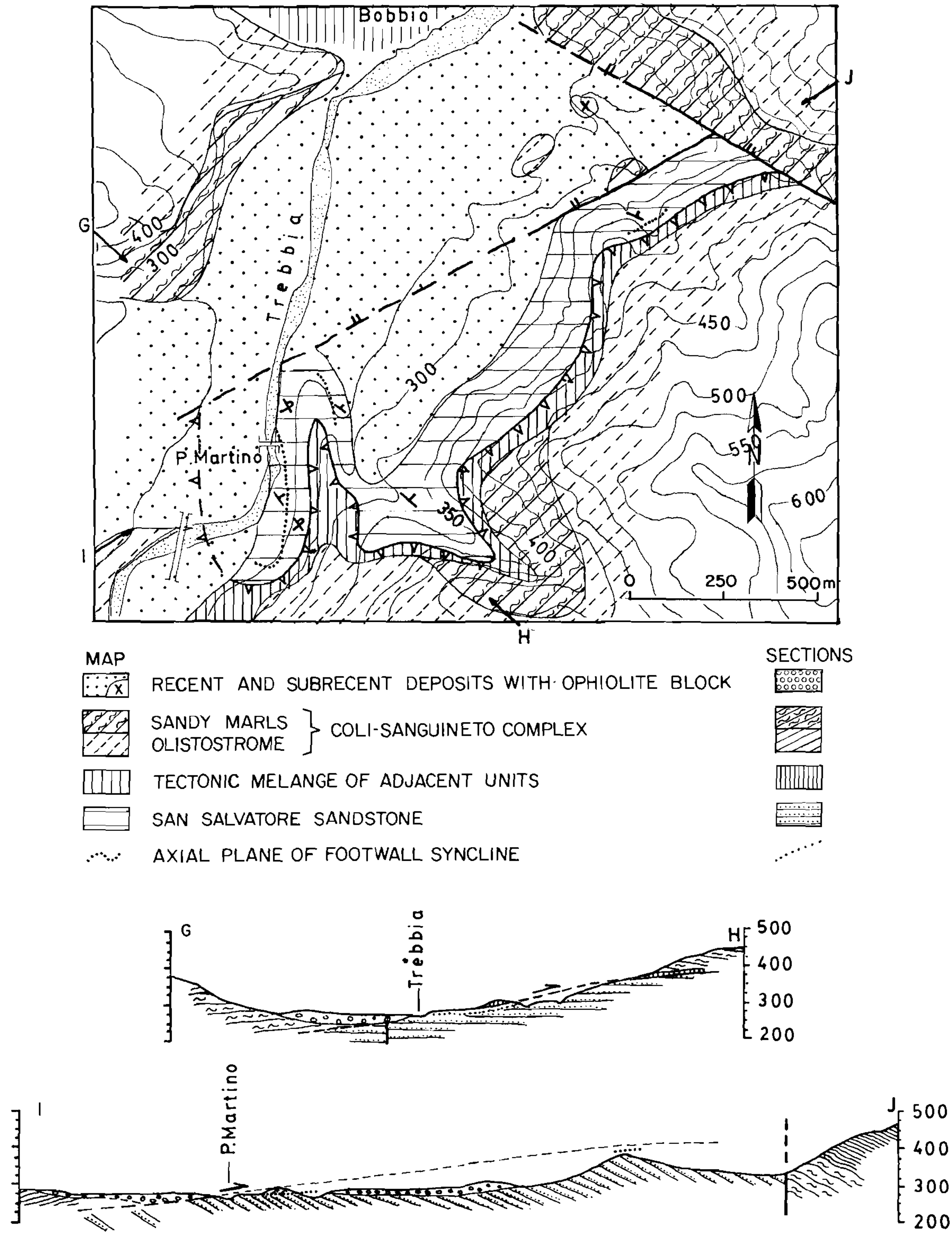


fig. 19 Geological map of the Trebbia valley between P. Martino and Bobbio, with cross-sections.

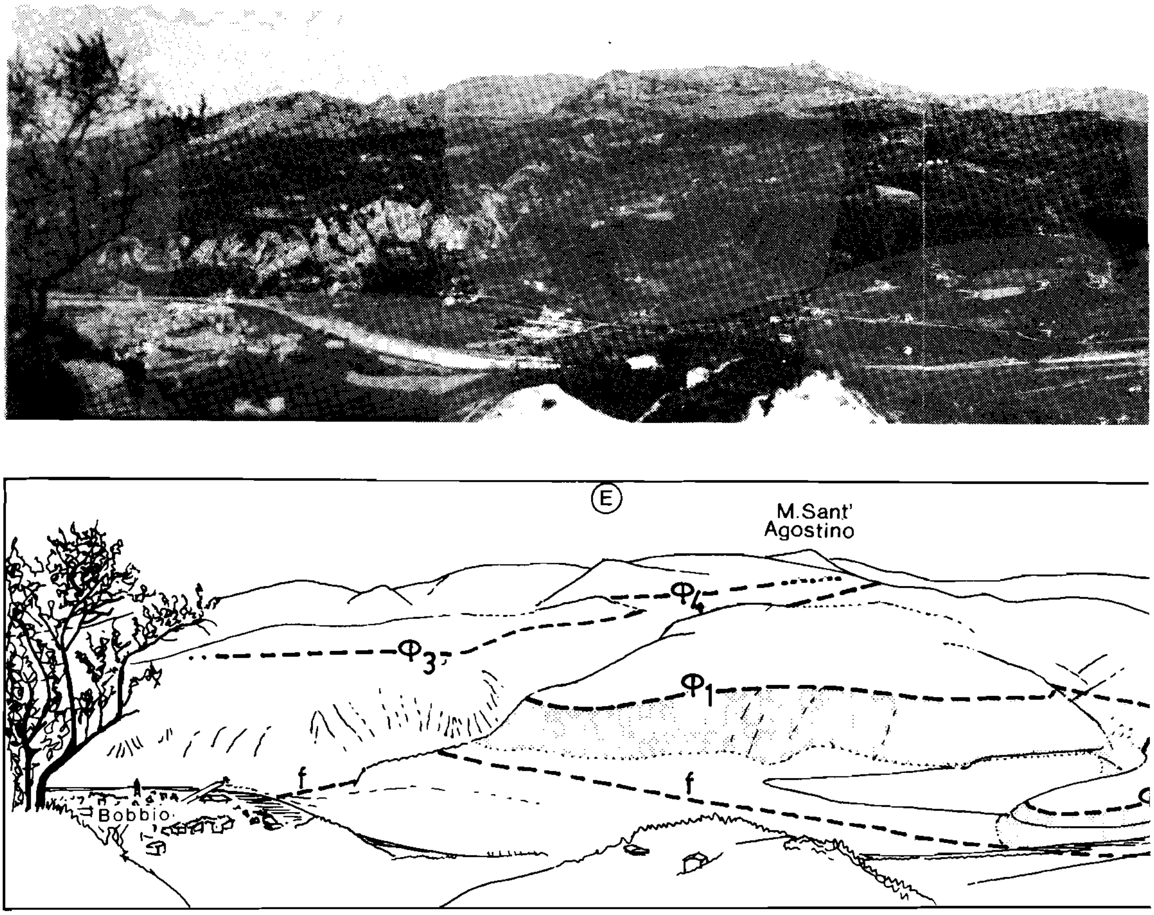
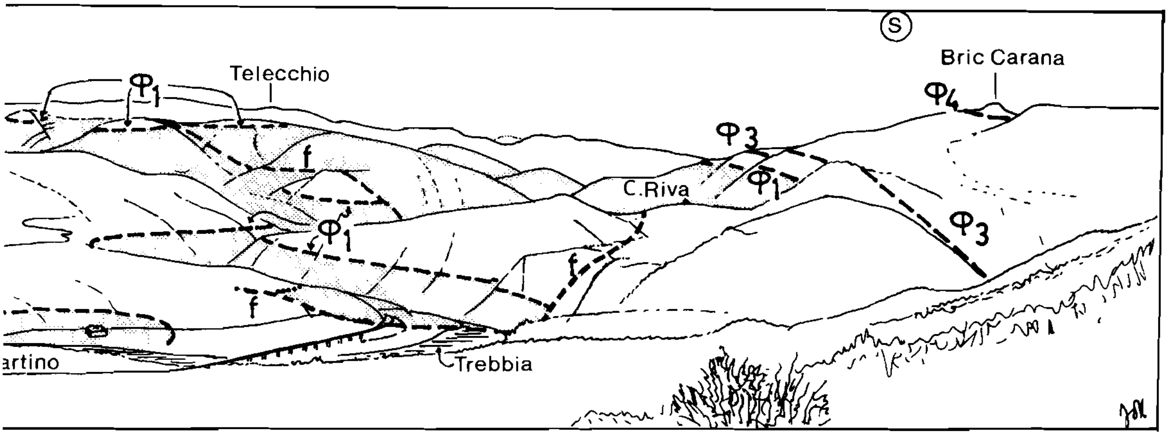


fig. 20 Panoramic view of the Trebbia valley between Bobbio (left) and Bric Carana (right). Shaded areas refer to outcrops of



San Salvatore Sandstone. The map on fig. 19 partly covers the area. Index numbers of the thrust planes match those mentioned on fig. 9.

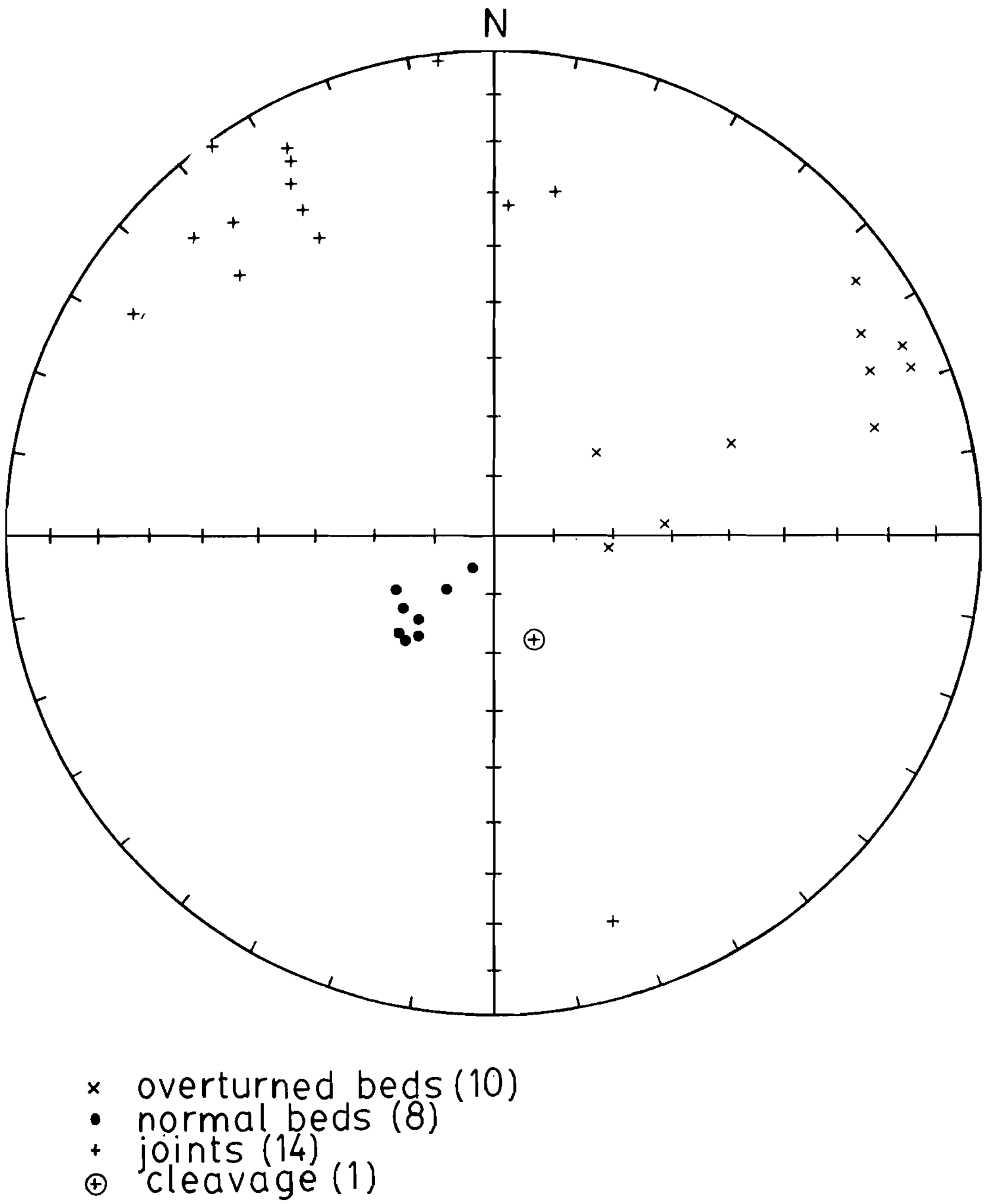


fig. 21 Bedding, joints and cleavage of the San Salvatore Sandstone near P. Martino. Lower hemisphere projections of poles in a Schmidt net.

26 Overthrust with little or no deformation of the San Salvatore Sandstone top

This case is schematically illustrated on fig. 15[c] and it is shown in the field in the Curiasca valley near Coli. Directly E of Castello Magrini the San Salvatore Sandstone dips at approximately 25° NNE. It is overlain by apparently homogenous yellowish weathered marls with a sharp contact. At closer examination the rock is fully criss-crossed by calcite veins, contains ball-like rolling structures and blocks of sheared and crushed limestone and sandstone. The section across this contact is, upwards from below (fig. 18):

- thick NNE-dipping beds of San Salvatore Sandstone,
- approximately 3 m of thinner bedded San Salvatore Sandstone, alternating with sandy marl beds. The sandstone is still undeformed but the marls are sometimes sheared.
- the thrust plane, sometimes cutting the underlying beds at an angle up to 5°.
- 4 to 10 m of yellow weathered marls, that are locally mixed up with streaks of dark shale from CSC-olistostromes. Blocks of coarse sandstone (San Salvatore Sandstone), bluish calcarenite (occasionally occurring in the Tuscan formations) and bright coloured micritic limestone (an olistostrome component) are concentrated in the marls near the thrust plane. This interval grades into:
- 5 to 11 m of still heavily tectonized marls of bright yellowish weathering colour. Here, boudins of marly limestone from the sandy-marly facies of the CSC are scattered through the rock.
- Olistostromes of the CSC. The lower contact is not exposed.

Deformation has taken place in the hanging wall only; the sandstone in the footwall is amazingly undeformed.

The mule path from Coli towards the bridge over the Curiasca torrent cuts another well exposed example of a similar

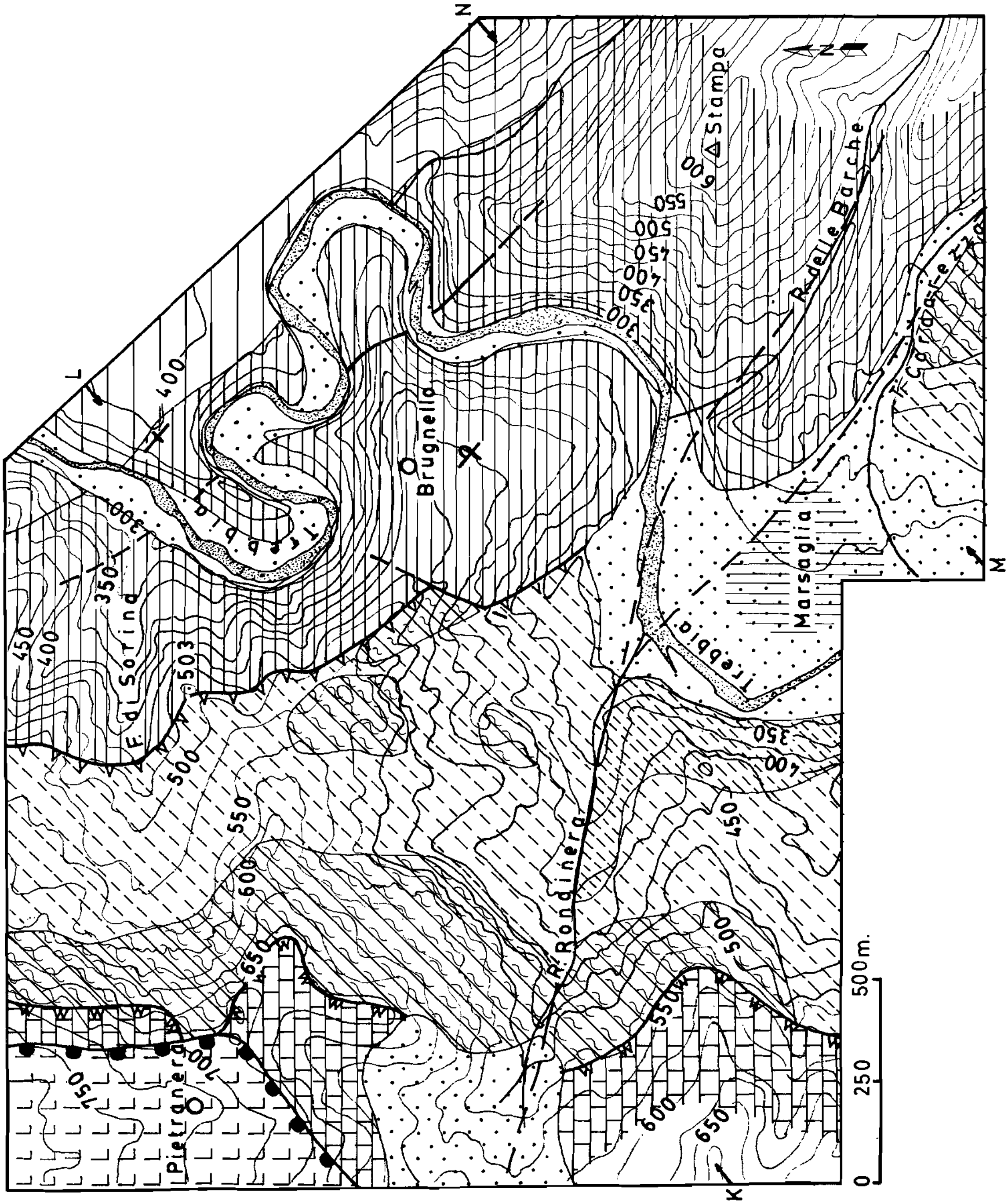
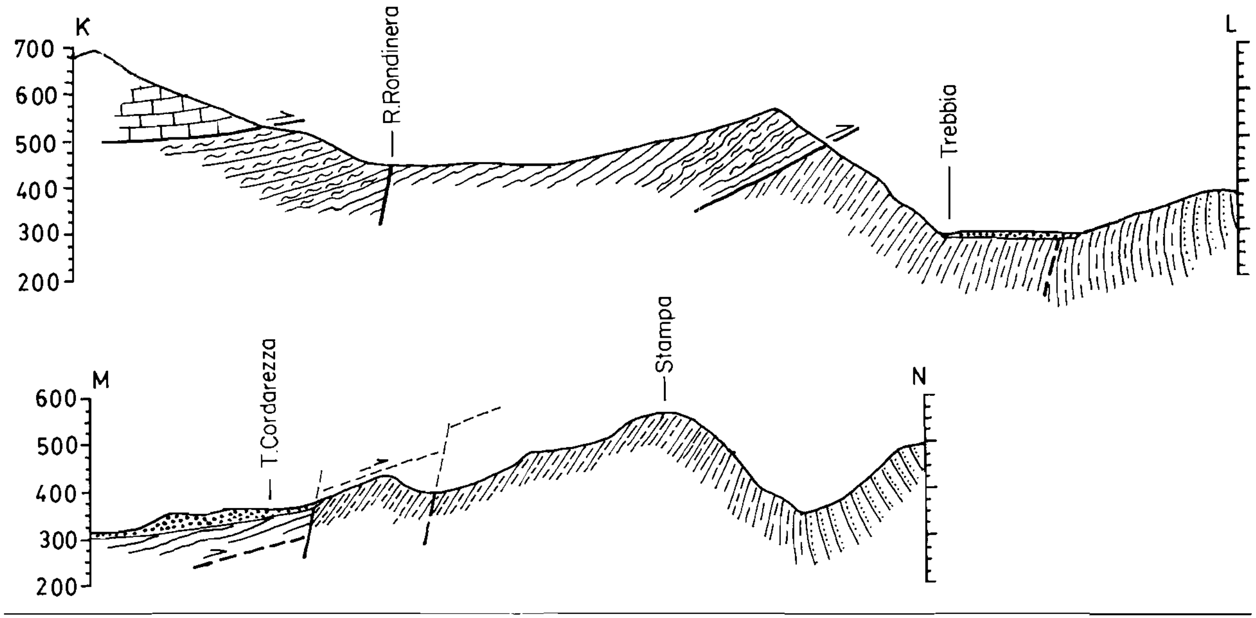


fig. 22 Geological map of the Trebbia valley in the Marsaglia-Brugnello area, with cross-sections.



SECTIONS MAP

DEBRIS, ALLUVIAL DEPOSITS

LIGURID COMPLEX

MONTE PENICE SEQUENCE

SANDY MARLS
OLISTOSTROME, MARSAGLIA OLISTOSTROME (a) } C.S.C.

SAN SALVATORE SANDSTONE
BRUGNELLO SHALE

LIGURID THRUST

PENICE THRUST

COLI-SANGUINETO THRUST

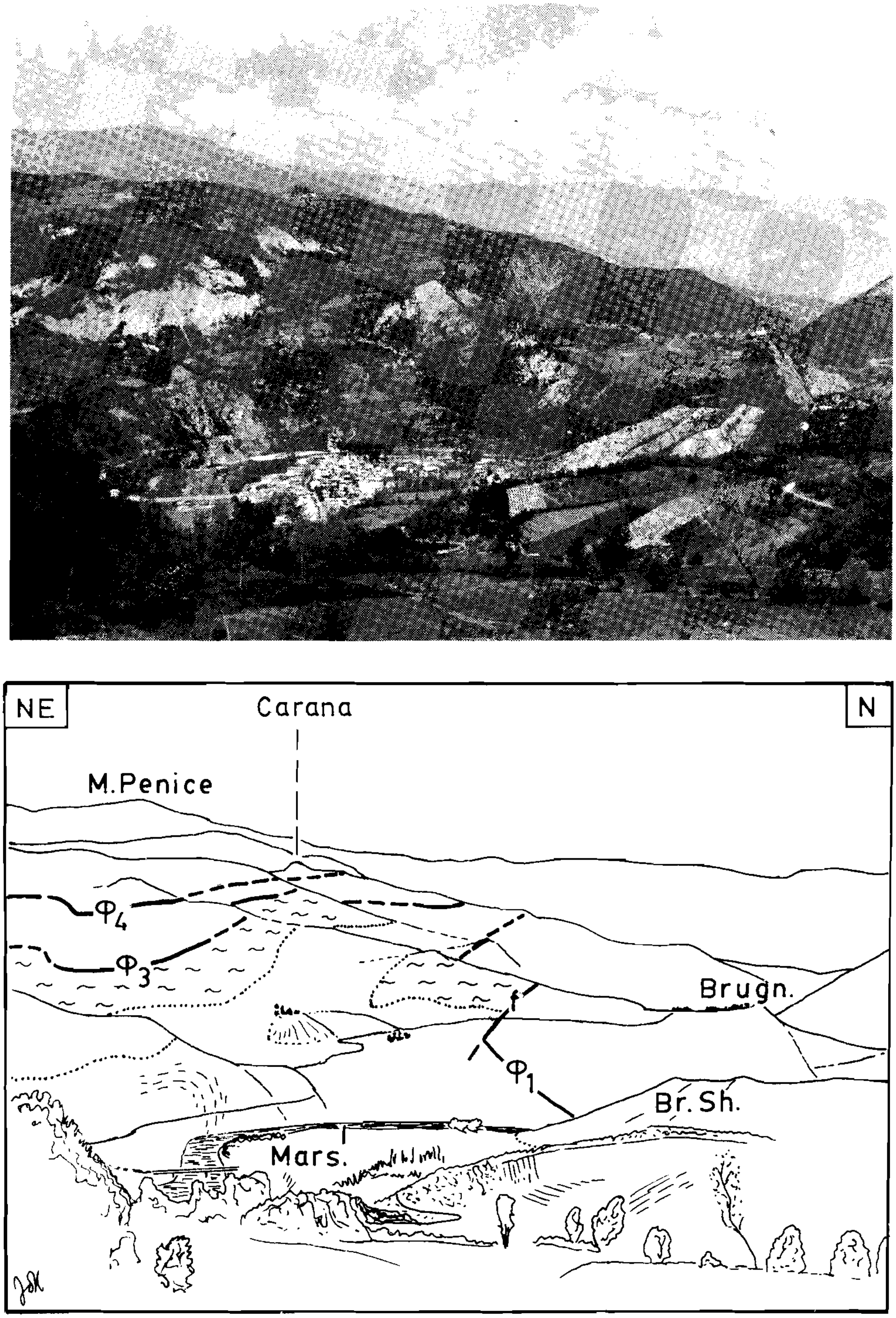


fig. 23 The Trebbia valley near Marsaglia viewed from the SSE.
See also the geological map on fig. 22.

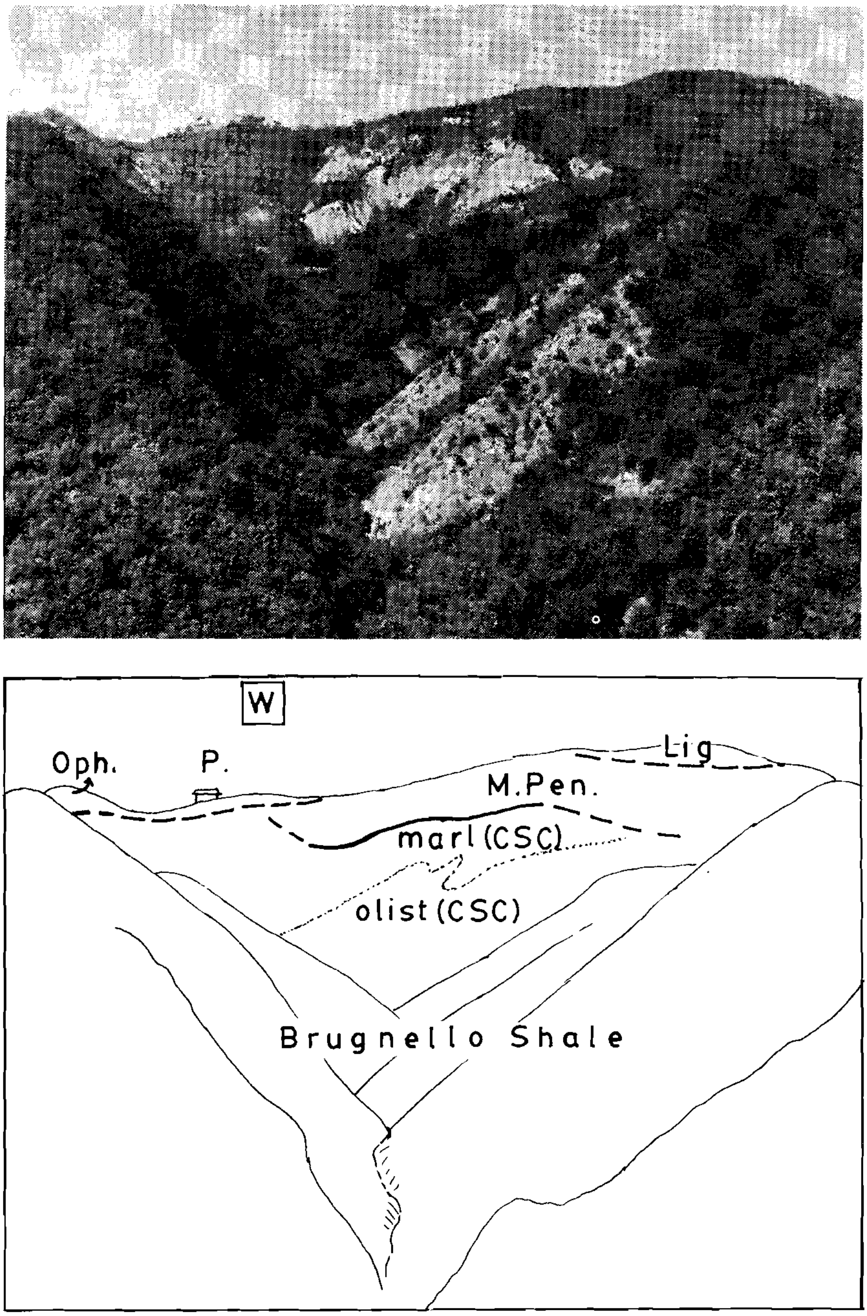


fig. 24 The Fosso di Sorina valley viewed due W from km 89.1 of S.S. 45. At left top is Pietranera. Compare fig. 22.

section: thick bedded San Salvatore Sandstone is overlain by 3 m of thinner beds, none of which have been notably deformed. Then follows a sequence of marls, black shale, bright limestone blocks and grey sandstone blocks that are all squeezed or heavily folded. The components are not as homogenized as in the Magrini section. This results in a more chaotic picture.

From Magrini eastward the tectonic contact remains very much similar. Only occasionally an intermediate form of deformation of the sandstone top has been observed (fig. 15b), e.g. on the right bank of the Curiasca, NNE of the Peli chapel (NQ $341^3 536^0$). Here, single sandstone beds have been torn loose from the footwall and dragged into an overturned position. Also, boudins of sandstone lie embedded in crushed marls.

27 The southern contact between the CSC and the Tuscan sequence. (figs. 22, 27).

This contact is generally badly exposed. A large stretch is covered by alluvial deposits of the Cordarezza torrent, that runs NW towards Marsaglia. In this direction exposures of the thrust contact lie near the 1000 m elevation in the M. Zuccharo, Piano di Robecco and Rio dei Frati area. At the left side of the Trebbia the contact is exposed in the Fosso di Sorina valley and near Brugnello (fig. 24).

The section at the Fosso di Sorina is (upward from below):

- unafflicted overturned Brugnello Shale,
- tectonized Brugnello Shale, cut by reverse faults,
- a chaotic interval with reddish weathered calcarenite blocks that originate from the Brugnello Shale,
- the thrust zone, in which a slab of well bedded sandstone-siltstone alternation is incorporated. Probably it is a small horse of Brugnello Shale.
- olistostromes of the CSC.

On hilltop 503, S of the Fosso di Sorina (NQ $300^{0}527^{6}$), disrupted blocks of coarse sandstone (presumably San Salvatore Sandstone), folded bed fragments and occasional boudinage are observed at the contact (fig. 25).

Between the Trebbia and hill 503 the contact is partly marked in the field by steeper slopes of the outcrops of the Brugnello Shale and it is lined by boudinage and local development of pronounced cleavage with attitude 120 - 80 SW.

The road section along SS. 45 N of Marsaglia exposes the lowermost Brugnello Shale. The bedding has fully gone by tectonics and occasional cleavage at 125 - 75 SW is present. The CSC-thrust plane is not exposed.

The most southeastern outcrops of Brugnello Shale are situated near Metteglia and Piano di Robecco (fig. 27). Following the footpath from T. Metteglia to Marsaglia, 90 m after the hill marked 958 a section is crossed in a folded variegated sandstone-shale alternation that gets progressively more contorted at the approach of a small saddle in topography. In the saddle we find the thrust plane between overturned SW-dipping Brugnello Shale and sheared rocks of the CSC. The latter are comparable to the "Peli Argillites" of the northern contact. To the S, this plane cannot be followed but it is fenced in by scattered outcrops of both units. It can be followed to the N by means of the sheared zone that is often accompanied by a break in the slope. It is offset by a steeply inclined WNW-ESE striking normal fault that is well exposed at the crest that leads down the M. Zuccharo to the N. Here, the Brugnello Shale is hardly deformed whereas the varicoloured sandstone-shale alternation is intricately folded, disrupted and criss-crossed by calcite veins. A squeezed interval with sandstone boudins is interposed between the two.

The normal fault is easily traced to the E. In the Rio Grande bed, 25 m above the crossing of the path Metteglia-Rosso the thrust plane reappears.

Folded marls and sandstones of the CSC overlie mildly deformed Brugnello Shale. Some SW-dipping cleavage is developed.
On the N rim of the Piano di Robecco the thrust plane is again marked by acutely steepening slopes.
N of the Piano di Robecco the path to le Barche crosses a completely exposed section through:

- crushed marls of the CSC, mixed up at the base with huge disrupted blocks of San Salvatore Sandstone (fig. 26),
- a slightly S-inclined thrust plane,
- a level of severely squeezed Brugnello Shale with flattened sandstone beds,
- steeply inclined San Salvatore Sandstone.

Just S of the beginning of this section we find outcrops of the overlying Monte Penice unit. The vicinity of the Penice thrust plane might account for the high degree of deformation of the whole section described.

We have already stated that N of M. Zuccharo a WSW-ESE trending normal fault offsets the Coli-Sanguineto thrust plane. The southern limit of the Tuscan outcrops in the Cordarezza- and Bastardino valleys is constituted by another normal fault. Although the latter is nowhere exposed, its existence is plausible because of the following observations:

- SW of the Bastardino torrent the Monte Penice thrust plane lies at a height of 800 m, whereas it is situated at about 1025 m north of it (cross-sections OP and RS, fig. 27);
- The Bastardino-Cordarezza bed forms a straight valley down to the confluence with the Trebbia near Marsaglia; it invariably separates Tuscan rocks from the CSC. This observation suggests a steeply inclined fault on geometrical considerations: if the CSC thrust plane would have continued its course through the Cordarezza valley, it would have required an acute bend in both strike and dip of the plane from 50 - 15 SE to 130 - 45 SW.

As there are no indications for secondary folding of the rocks that underlie the thrust plane, this latter supposition should be rejected.

28 Interpretations by other authors

Mutti and Ghibaudo (1972) stated that the San Salvatore Sandstone is overlain by allochthonous terrains (the Coli Complex), but they considered the overturned lower contact of the Brugnello Shale as an original surface of stratigraphic onlap of fan fringe turbidites over the basin floor consisting of slope deposits matching the "Complesso di Sanguineto" of Bellinzona et al. (1968). There are some serious objections against this picture:

- The Brugnello Shale is entirely overturned. In case of a stratigraphic onlap, its substratum should be overturned as well. The "Sanguineto Complex" lining the Brugnello Shale, it is true, yields little information about the bed position; when, however, indications are found they point to a normal position.
- The deformation of the Brugnello Shale in the Fosso di Sorina and near Brugnello and Marsaglia cannot be accounted for by a low-energy process like stratigraphic onlap.
- Sheared blocks of Tuscan sandstone have been found not only along the northern outcrops of the CSC thrust, but also the southern ones. They indicate the presence of Tuscan sandstone in more internal, buried parts.
- Outcrops of the CSC in the N and S are lithologically similar.
- They both bear vast amounts of olistostrome deposits that mainly consist of shales. In case of an onlap, why does the Brugnello Shale lack these olistostromes? We have only found intraformational slumps in it.

If we accept an overthrust by a single CSC, these objections are dealt with.

Fig. 25 Sheared block of San Salvatore Sandstone found at summit 503; right slope of Fosso di Sorina. Diameter of coin is 2.5 cm.

Fig. 26 Sheared blocks of San Salvatore Sandstone exposed near the Coli-Sanguineto thrust plane N of Piano di Robecco.

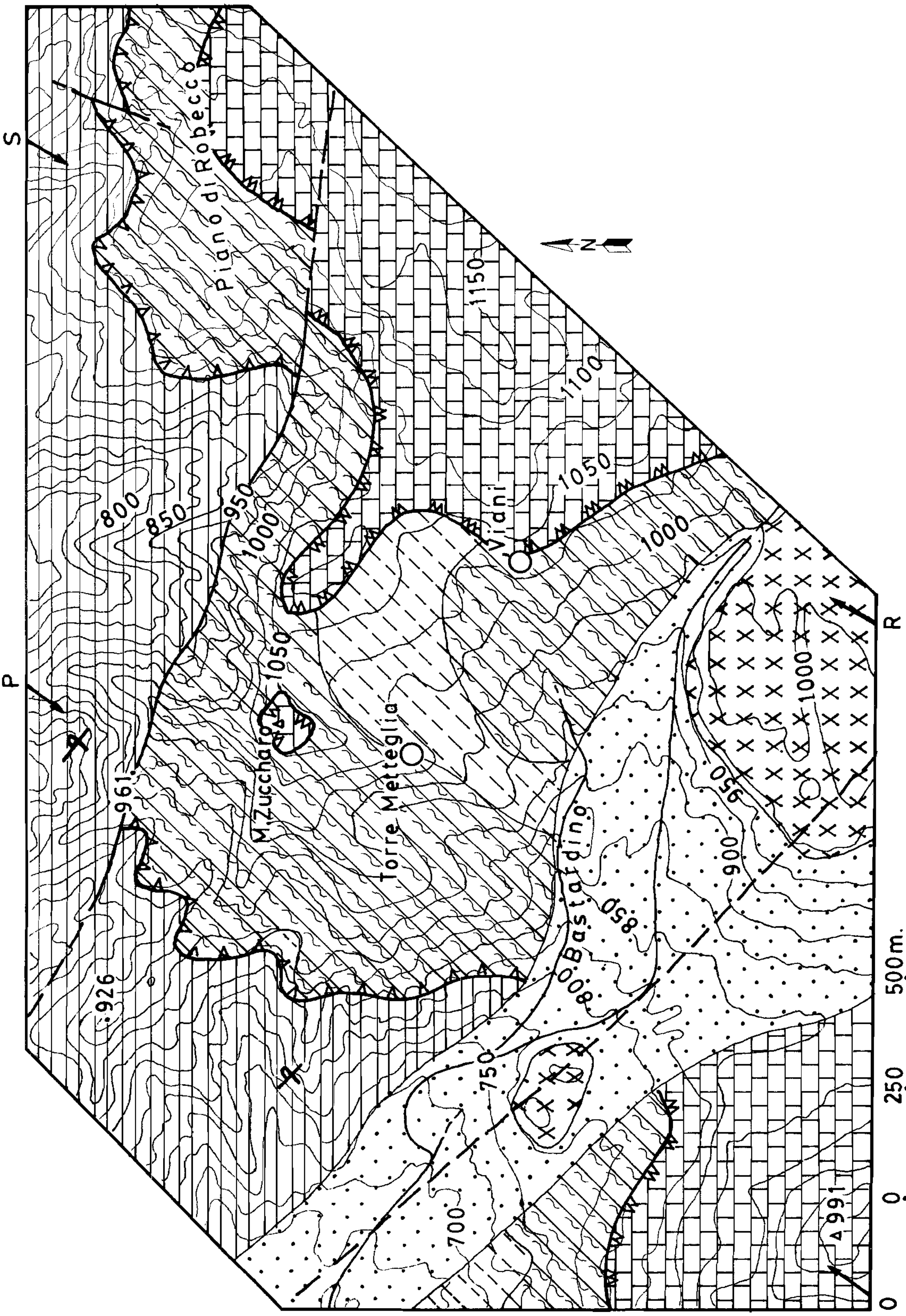
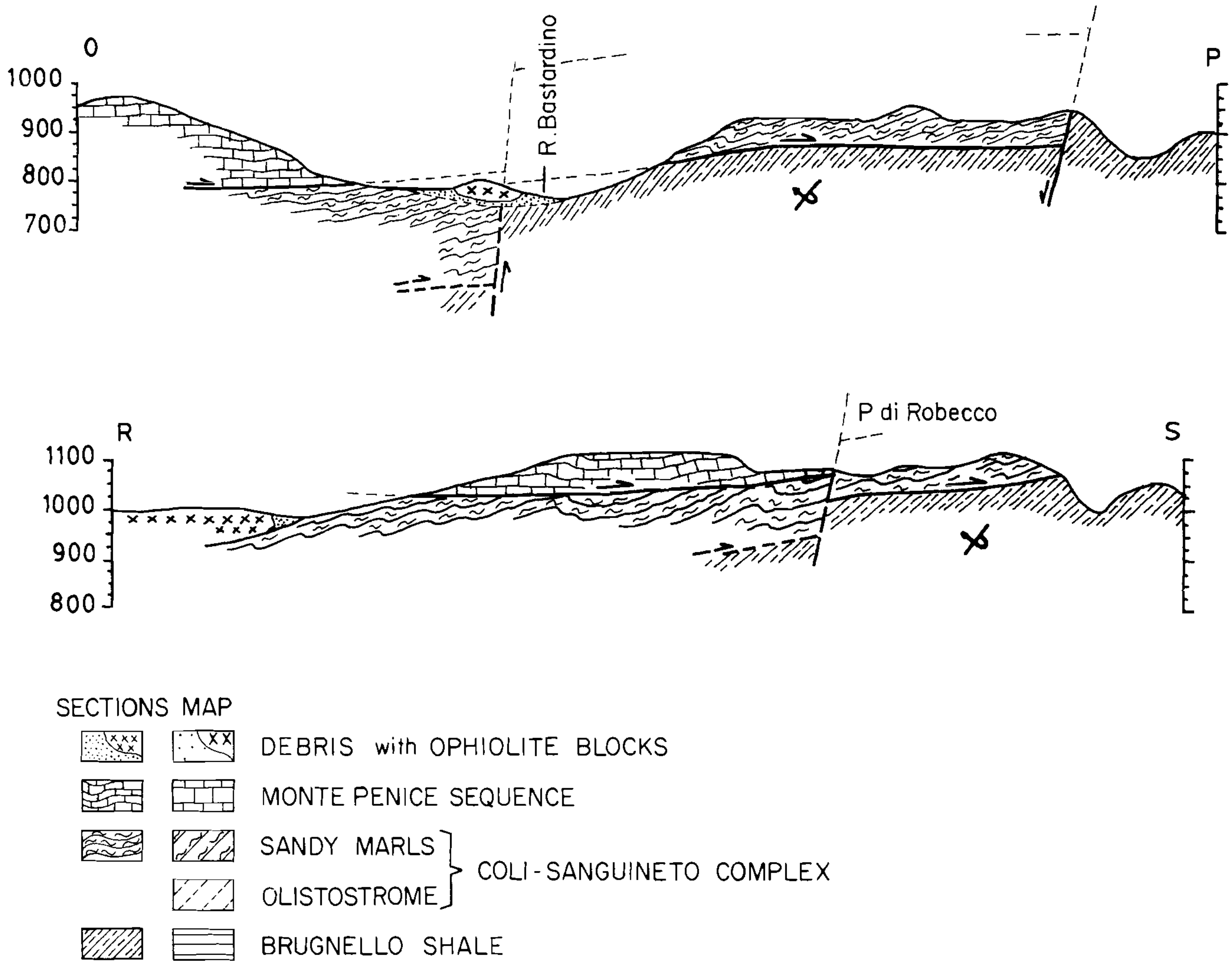


fig. 27 Geological map of the M. Zuccharo-Piano di Robecco area, with cross-sections.


O
P
1000
900
800
700
R. Bastardino
R
S
1100
1000
900
800
P di Robecco
SECTIONS MAP
DEBRIS with OPHIOLITE BLOCKS
MONTE PENICE SEQUENCE
SANDY MARLS
OLISTOSTROME
COLI-SANGUINETO COMPLEX
BRUGNELLO SHALE

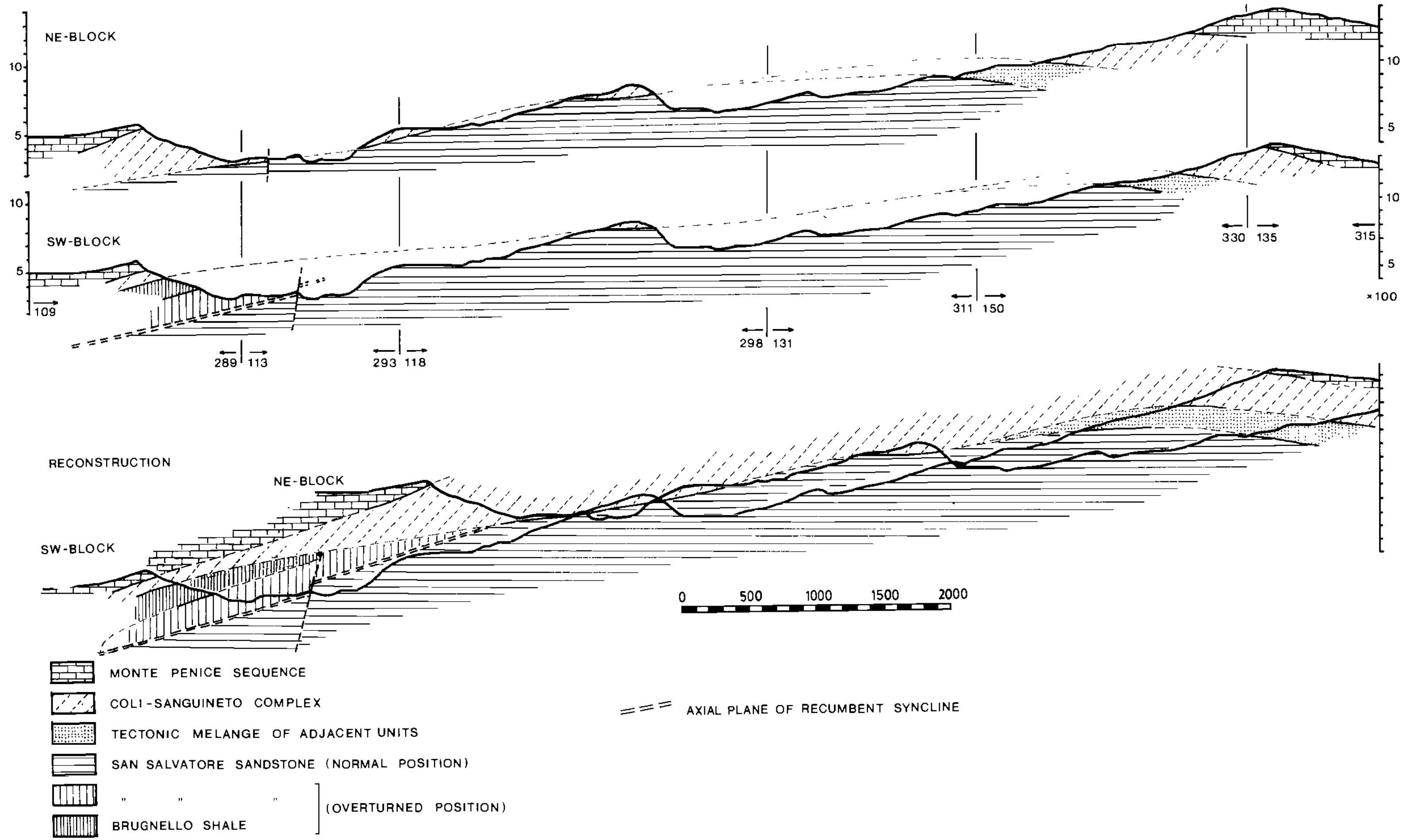


Fig. 28 The San Salvatore Fault. The construction shows the intersection of the NE- and SW blocks with the fault plane. A pre-fault reconstruction is also given.

29 The San Salvatore Fault

In cross-section AB of fig. 16 it is evidently impossible to re-create the pre-fault situation by shifting back the blocks vertically; if we move back the San Salvatore Sandstone a conspicuous misfit of the overlying formation is the result. Various stages of reactivation of the fault also lead to elaborate, unsatisfactory interpretations. The only way to comply with the terms set by the observations is to assume a strike-slip fault.

Fig. 28 shows a construction in the fault plane of the intersections with both north- and south blocks and their

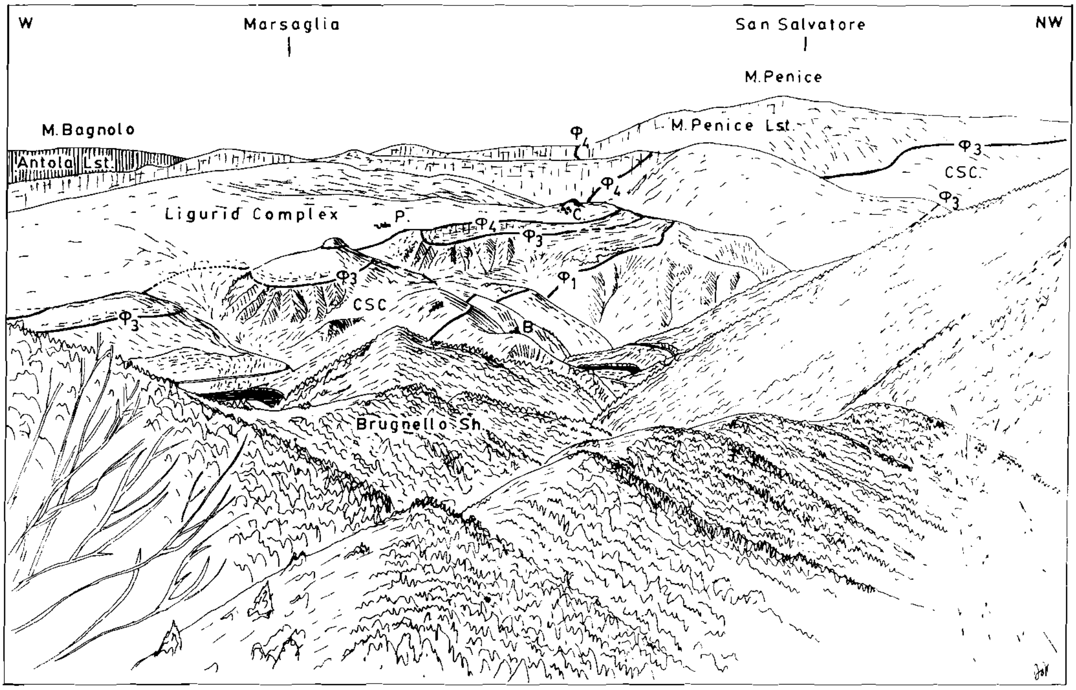


fig. 29 Panorama of the Trebbia valley viewed from point 906 located 500 m NW of M. Zuccharo. The overthrusts are clearly shown. Note the Antola Limestone (top left) and the changing thickness of the Monte Penice unit.

reconstructed fit. The result is a sinistral strike-slip fault with a net slip of about 2000 m. At the eastern border of the window the vertical component has decreased from about 550 m to 100 m.
The tectonic regime favouring such a wrench fault existed in Late Miocene or Early Pliocene times. In section IV a connection will be postulated with sinistral strike-slip movements along the Varzi-Villalvernia lineament and with the relative eastward motion of the Antola slab.

The Canetolo Complex

30 Coli-Sanguineto Complex

In the previous section we have argued that the CSC, the lowermost sub-unit of the Canetolo Complex, has overridden the Tuscan sequence; apart from deformation of the footwall there are more arguments: the ages of both CSC and the Tuscan sequence overlap, yet they are quite distinct sedimentologically and lithologically.
The sharp lithological difference between the alternating facies within the CSC (the sandy-marly facies and the chaotic shaly facies) explains why the competent sandy-marly intervals remain relatively unaffected by strain and why the strain will be released preferably in the plastic olistostromes. Probably, a dismembering of the thrust sheet into smaller and more uniform competent units has taken place, using the olistostrome shales as sliding levels. This is illustrated by the presence of olistostrome shales along the major part of the CSC thrust plane, either mixed with other components or not (section 13).
It is not possible to reconstruct former stratigraphic relations within the dismembered CSC because:
- we are short of markers labelled by age data or by

recognizable sedimentary successions,

- the outcrop rate is very low, especially of the olistostromes. Moreover, landslides (frane) are very active and slided olistostromes are hard to distinguish from the ones in situ.

In the northern outcrop area, dips towards the S are predominant. In the sandy-marly facies the dips are evident when turbidite beds are present. In the olistostromes a SW-dip is often suggested by orientation of planar rocks fragments embedded in the shales. This orientation not necessarily represents primary flow banding within the olistostromes; it may as well have been formed tectonically. In many cases this planation is roughly parallel to the bedding in the sandy-marly facies or to the CSC thrust plane.

In the northern outcrop area the thrust plane dips predominantly to the NNE and NE. Clear NE-dipping planations have been observed only on the right bank of the Curiasca. Further to the N no preferential orientation of rock fragments in the olistostromes has been noticed and the sandy-marly member of the CSC shows no consistent trend at all in the bedding planes.

Concluding, we believe that the Coli-Sanguineto Complex consists of a number of thrust slices, imbricated during gravitational transport. It has overthrusted and truncated the Tuscan sequence.

31 The Ruffinati Siltstone

The Ruffinati Siltstone bears a fair similarity to the CSC. Sandy, marly and silty rock types, as well as the same kind of olistostromes, occur in both formations, though in different proportions. In our opinion both units originate from a common depositional basin, but their relation has been obscured. In the Ruffinati Siltstone deformational features are more easily to be found than in the CSC; due to the scarsity of olistostromes the relief is steeper and the outcrops are more

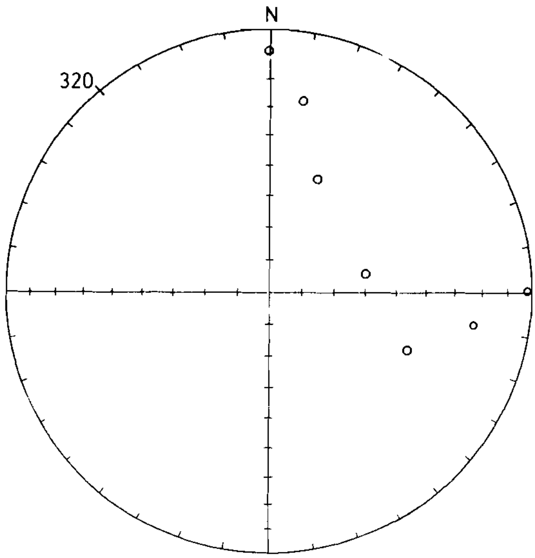


fig. 30 Some folds axes from the Ruffinati Siltstone, plotted in a Schmidt net. Lower hemisphere projections. The general Apenninic trend (320) is indicated for comparison. These fold axes contradict Maxwell's (1963) statement that the Ruffinati Silststone (= Val d'Aveto Formation p.p.) has only been afflicted by simple folding around a NW axis.

continuous, especially on the right side of the Aveto river. Although no fold hinge is exposed the bed attitudes indicate a NW-SE striking anticline in the Aveto valley. Apparently, these NW-SE strikes have been overprinted on older structures. The older deformation involves isoclinal folds (NQ $308^{8}465^{5}$, $307^{0}468^{9}$), kink folds (km 6.85 - 7.7 of S.S. 586) and other steeply plunging folds (km 5.7). They are plotted in fig. 30. The amplitude of the NW-SE folding considerably larger than that belonging to the older phases.
The contact with the CSC is tectonic. It is exposed between km 84.25 and 84.5 of S.S. 45, S of the Confiente bifurcation. Marls and olistostromes of the CSC are overlain by boudinaged and

sheared siltstones of the Ruffinati Siltstone.
The contact with the Aveto Sandstone is disturbed but transitional. It will be discussed in the following chapter.

32 The Aveto Sandstone

The lower boundary of the Aveto Sandstone is transitional but disturbed by strongly tectonized levels. This is obvious since the recent incision of the road Ruffinati-Lisore was completed. Some of the sheared intervals are exposed in the road section S of the power station at Ruffinati:

- The lower part (up to km 12.92) is typified by thin intervals of bright grey-greenish shales, interbedded between sandstones and siltstones. The latter are not very deformed but the shales are usually crushed to small scales and "slate pencils". The above meant succession, probably still Ruffinati Siltstone, is overlain by an unexposed interval. Afterwards a change in lithology has taken place: squeezed red shales with silicious limestone beds in contorted beds and boudins appear. Patches of green, coarse sandstone and red jasper lie within the shale. The overlying rocks are sandstone beds folded around an axis of approximately 300^{o}, interbedded with strongly deformed greenish-grey shales. The next 40 m include gradually coarsening sandstones in a roughly monoclinally SW dipping position. Slickensides at some minor fault planes indicate reverse faulting towards the NE.
- The unexposed interval near km 13 can be picked up at the left bank of the Aveto. It includes shales interbedded with layered sandstones and massive coarse grained sandstones. Locally, they have been severely deformed. A badly exposed interval divides this sequence from the lowermost clear Aveto-type sandstone. No limestone beds are present in this section.

There are two more sections exposed to some extent:

- The path from Ruffinati to Cattaragna and thence to Curletti: The first Aveto-type sandstone including conglomerates lies at an altitude of 690 m. Lower, dark grey, fine grained sandstone of the Ruffinati Siltstone has been observed. SW-dipping cleavage has been developed in it.
  Along the first 500 m of the road Cattaragna-Curletti we have observed various rock types, all crushed or boudinaged: grey micaceous sandstones dark grey sandy marls, bright grey greenish shales and micritic limestones.
- On the old mule path from Ruffinati to Lisore the most conspicuous feature is the particularly sheared interval at 75 m above the Aveto bed level. It includes sandstone boudins surrounded by sheared shales. The thickness of the level is appr. 25 m.
  The new road exposes similar shear zones with shales and boudins. Just underneath Lisore the first coarse conglomerates lie as boudins in thin-bedded sandstone-shale alternations.

33 The Monte Penice unit

The Monte Penice unit is the oldest sub-unit of the Canetolo Complex. According to various authors (Braga, 1965; Abbate et al., 1970; Plesi, 1974, 1975, 1975[a]) it has been affected by folding and block faulting during the Eocene. This is demonstrated by angular unconformities and coarse detrital sedimentation.

Scattered, discontinuous slabs of the M. Penice unit tectonically overlie the Oligocene and Miocene units of the window of Bobbio, the windows of the upper Nure valley and the Taro window.

The Santa Maria Shale has served as a sliding level. The shales occupying a position next to the overthrust tend to be darker coloured and more indurated than they normally are. The Monte

Penice Limestone in the type locality has been folded into overturned folds with a strong NE vergence: this is obvious in the road section from S. Maria to Ceci and near Menconico on the W slope of M. Penice. In the numerous smaller exposures that border the Oligo-Miocene of the window it cannot be demonstrated because the rocks are merely tectonized slices between the Monte Penice- and the Ligurid thrust planes.

34 Deformation of the footwall of the Monte Penice thrust

The Monte Penice thrust has truncated the underlying units, and consequently, also the tectonic contact between the CSC and the Ruffinati-Aveto unit.
It is nowhere seen to overlie the Tuscan sequence.
The thrust plane is usually badly exposed due to landslides in the Santa Maria Shales. There are some exposures, though:

- At both sides of the T. Carlone valley turbidite intercalations of the CSC underlie the thrust plane. They are folded into a syncline with an ENE vergence and an overturned SW limb. The size of the structure is some tens of m. We interpret it as a drag phenomenon related to the overthrust. We have not observed other similar structures.
- The road incision of S.S. 45 between km 81.5, E of Lenzino exposes sheared limestones and shales from the hanging wall mixed up with sandstones from the footwall.
- After the first left hairpin of the road ascending from S.S. 45 to Lago, lie exposures of shaly rocks with blocks of coarse-grained, greenish sandstones and of olistostrome breccia containing ophiolite fragments. The shaly rocks are in the "calcare e argilla" facies. The olistostromes are most probably derived from the Monte Penice Limestone. The coarse greenish sandstone is macroscopically similar to sandstones exposed at the base of the Aveto Sandstone in the Aveto valley.

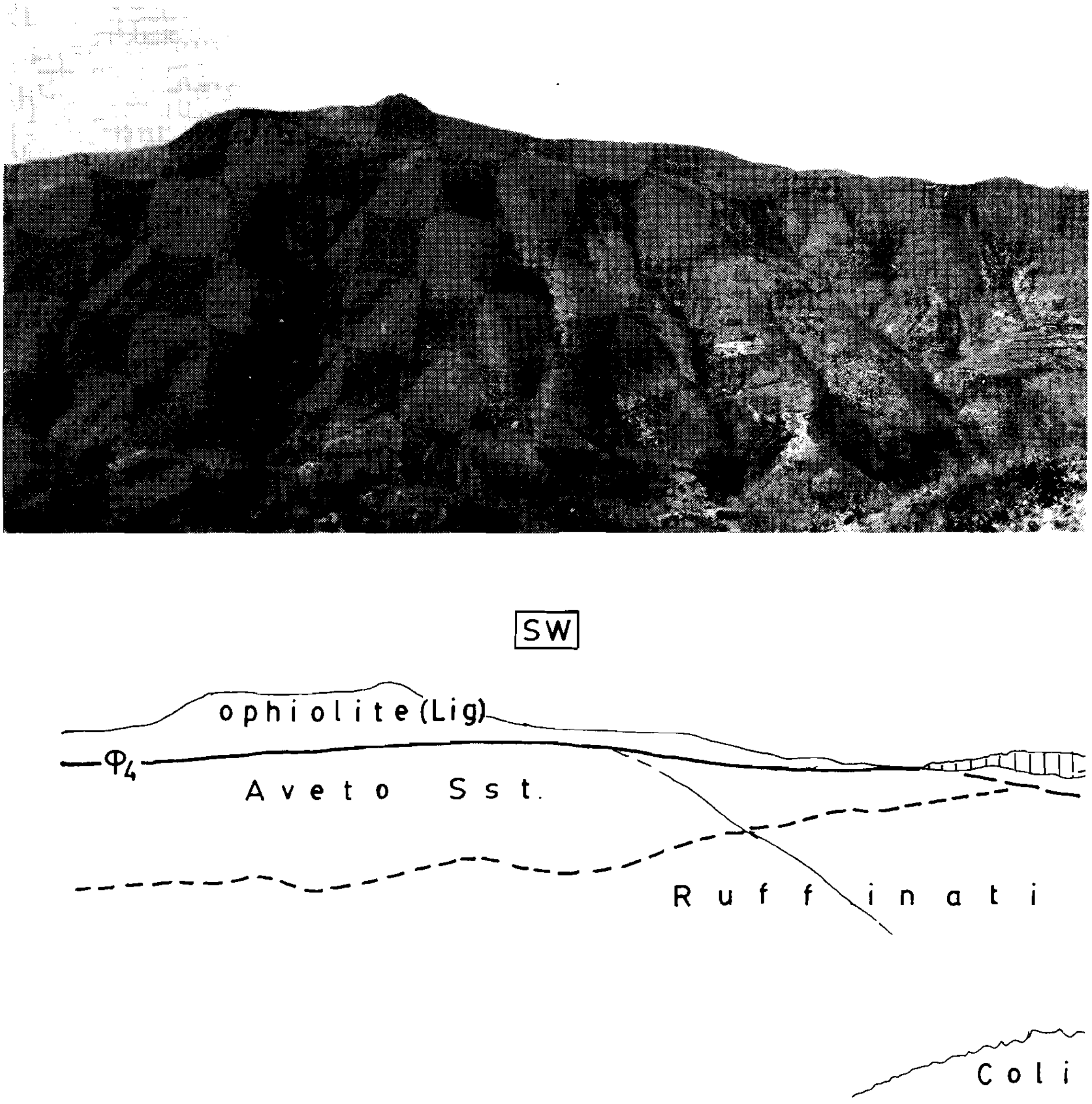
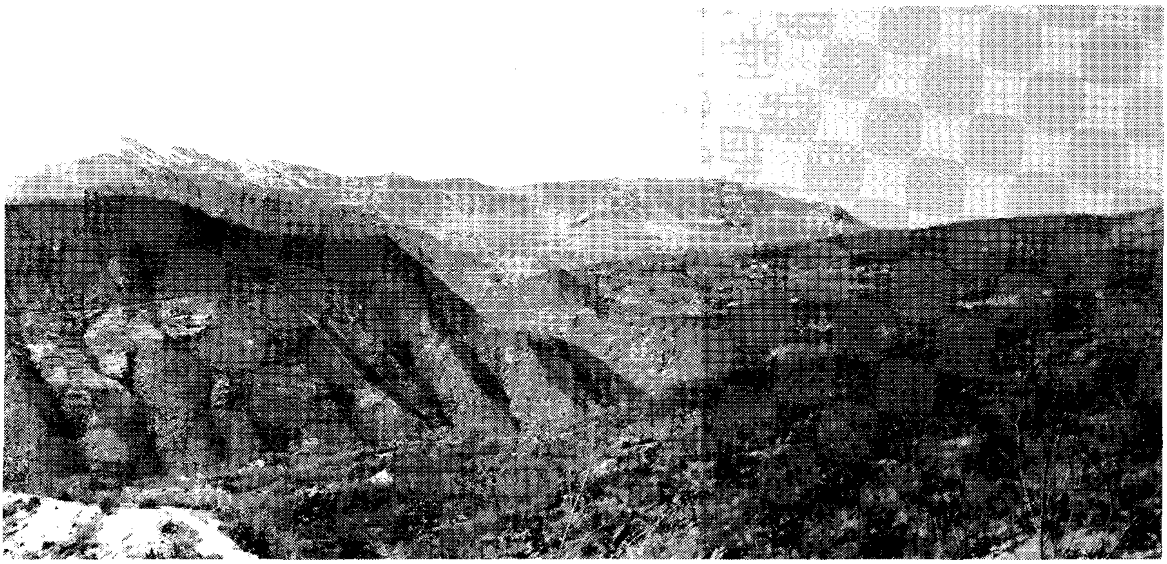
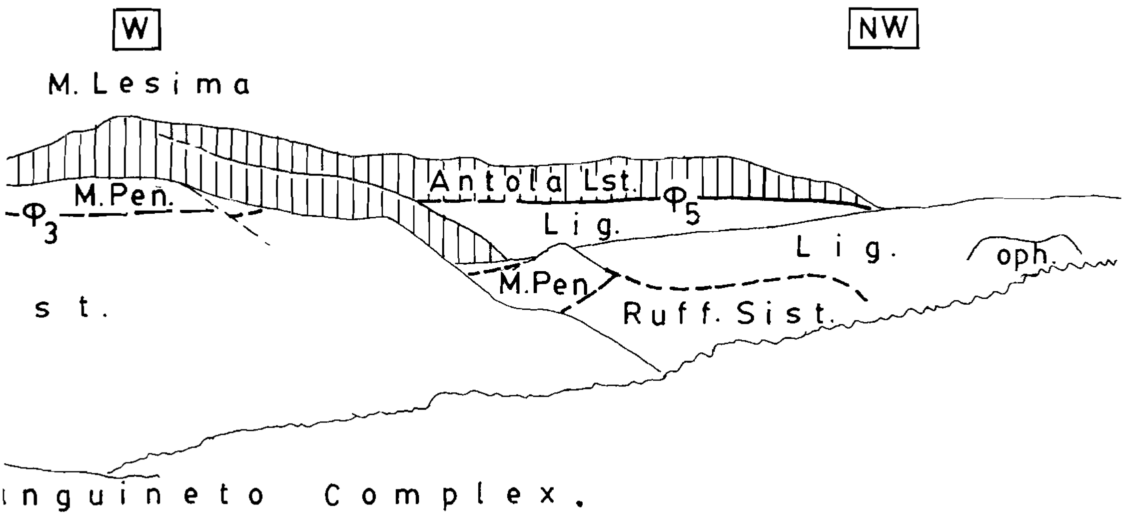


fig. 31 Panoramic view of the lower Aveto valley and the Aveto- Trebbia





confuence seen from the E.

Microscopic similarity was also striking but in the samples taken from the Lago exposure the grain rims have been altered.
These chaotic exposures cannot be regarded as olistostromes in the Ruffinati Siltstone because of the presence of blocks of the younger Aveto Sandstone. We regard them as a slice of tectonized Santa Maria Shale of the Monte Penice thrust sheet mixed up with blocks picked up from the footwall. The picture has been obscured by landsliding.

35 Other authors

According to Plesi (1974), two slabs of calcareous flysch formations of Paleogene age are present in the window of Bobbio (fig. 32[a]):

1. The Monte Penice unit, which tectonically overlies the CSC. It is unconformably overlain by the Ruffinati Siltstone and the Aveto Sandstone. This unit is overridden by:
2. The Vico unit, which has small lithologic differences with 1. Both units are overlain by the Ligurid Complex. Thus, according to Plesi, the Canetolo Complex includes three sub-units:
   the Vico unit,
   the Monte Penice/Aveto unit,
   the Coli-Sanguineto Complex.
   They overlie the Tuscan sequence.

We have some objections against this interpretation:

- The intercalation of M. Penice-type Limestone cropping out N of Confiente underlies an especially contorted zone of micaceous siltstone-shale alternations with boudinaged, even grained sandstone beds in apparently normal attitude. In Plesi's concept a contorted zone is rather expected to overlie such a shear zone.

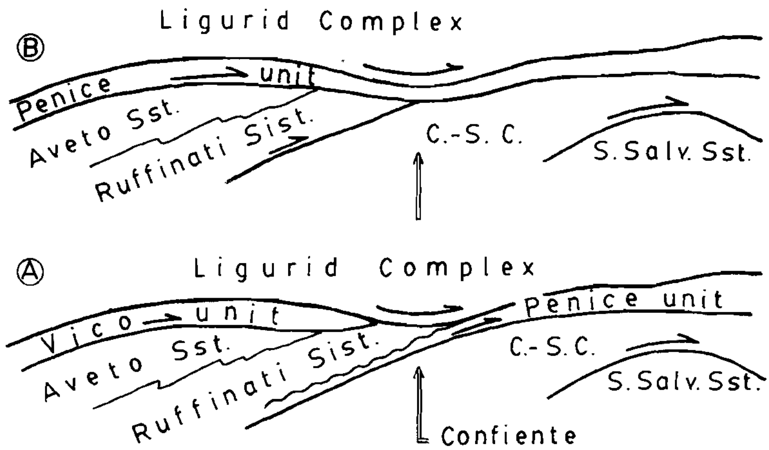


fig. 32 Superposition of sub-units of the Canetolo Complex.
A) according to Plesi (1974);
B) present interpretation.

- The M. Penice Limestone is nowhere overlain by the Ruffinati Siltstone or comparable rocks except at this tectonized contact near Confiente.
- The tectonic contact between the M. Penice- and CSC units as figured by Plesi does not systematically separate two different lithologies. In our opinion, the map by Bellinzona et al. (1968) is more acceptable at this point.

For these reasons we prefer the order of tectonic superposition represented in fig. 32^b.

36 The Ligurid Complex

We have not particularly investigated the Ligurid Complex. It is usually strongly deformed, especially at the base where the bedding has often been completely destroyed. The huge masses of ophiolite present in it are also tectonized. Near P. di Barberino, on the left bank of the Trebbia graded deposits in nonconformable

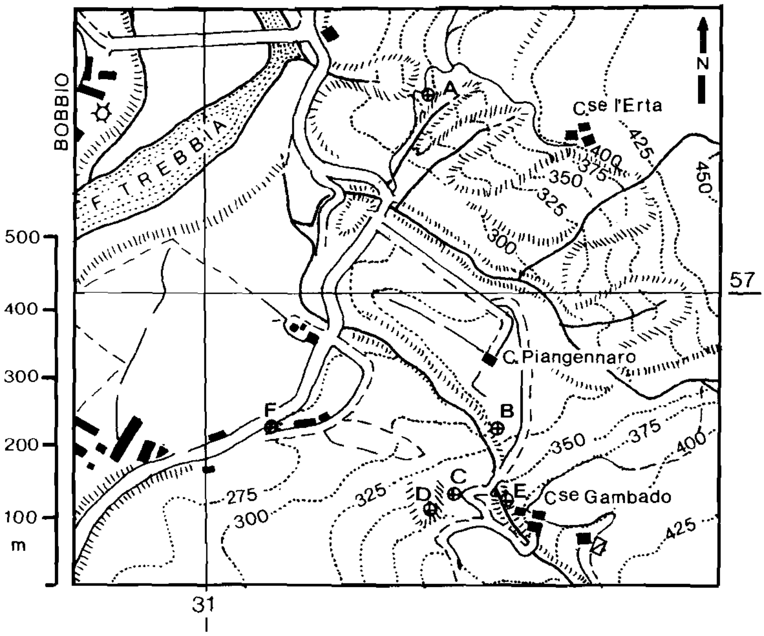
contact with an ophiolite mass demonstrate an overturned position; this also demonstrates the presence of ophiolites at the Ligurid basin floor in early Cretaceous times.
Structural trends are hard to delineate; this is indicated by Maxwell (1963): "..overturning and overfolding to the NE has been first refolded about northwesterly and later about a northeasterly axes".
The Ligurid rocks are extremely liable to landslides, as clearly illustrated by the Grattara ophiolite mass on the right bank of the Aveto river, the slided ophiolites at the upper Bastardino valley and the chaotic morphology of the Ligurid terrains. The slides are evident on aerial photographs.

37 Fault orientation

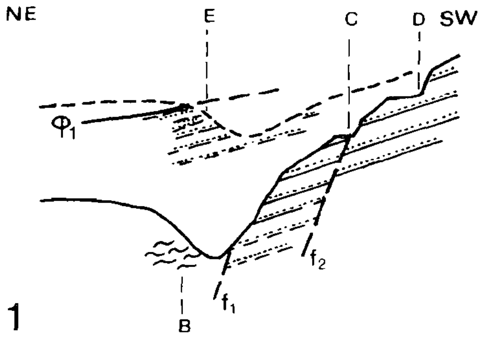
The entire pile of thrust sheets has been cut by two sets of faults, one in the Apenninic direction (NW-SE) and another at approximately right angle.
a) NW-SE trending faults.
These faults are steeply inclined and have throws of the order of several hundreds of meters.
The Barberino fault, bordering the window to the N, lowers the NE block at least 200 m.
The fault running to the SE from Bobbio juxtaposes the CSC and the Ligurid Complex. Consequently, its throw is about 200 m, being the estimated thickness of the variable Monte Penice sheet.
It is not clear if this fault extends into the window beyond Bobbio; this is suggested by a SE-NW topographic lineament.
We have discussed the San Salvatore Fault as a sinistral strike-slip fault (section 29; fig. 28).
The southern limit of the Tuscan outcrop is determined by downthrowing of the SW fault blocks, evident by the juxtaposition of different formations and by jumps in the elevation of the

Monte Penice thrust plane. The M. Zuccharo reverse fault has a throw of approximately 100 m and the Cordarezza-Rondinera reverse fault of 200 m in the SE and slightly less in the NW.
An other NW-SE striking fault starts NE of Salsominore and continues across the Ligurid terrains into the Pertuso window in the upper Nure valley. Its NE block has been downthrown approximately 200 m there.
b) NE-SW striking faults (transversal direction).
We have found but a few faults of this set, all of which have only small throws.
The large Tuscan outcrop in the Trebbia valley is limited to the N by a small transversal fault that downthrows the NW block. Its throw is several tens of meters.
The fault that constitutes the NW border of the small northern window of Tuscan outcrops (figs. 12, 19, 33) is disputable. It is based upon the juxtaposition of a sandstone-marl alternation of the CSC exposed at 100 m S of C. Piangennaro (NQ $314^1 568^0$; B on fig. 33) and topographically more elevated outcrops of San Salvatore Sandstone, 10 m to the SE (C, D and E on fig. 33).

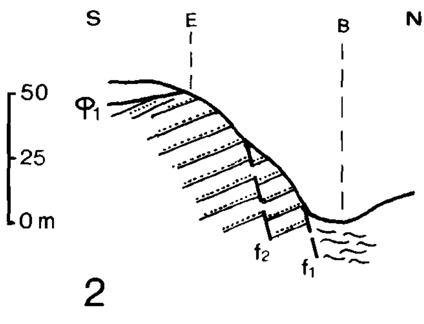
The eye-shaped form of the Tuscan core of the multiple window of Bobbio is not due to axial dip of the large recumbent syncline; bedding measurements plotted in a stereogram do not indicate such (fig. 34^a). More probably, an echelon of smaller A-C faults is responsible. One of these faults, W of San Salvatore, downthrows the axial plane of the recumbent syncline at the NW side: the overturned beds on the left bank of the Trebbia are juxtaposed to NE-dipping beds of the normal limb (figs. 16 and 28).
Field effects may also contribute to the eye-shape of the outcrop.



BOBBIO
F. TREBBIA
A
Cse l'Erta
425
400
375
350
325
300
450
57
500
400
300
200
100
m
C. Piangennaro
B
F
350
375
400
275
300
325
C
D
E
Cse Gambado
425
31
N



NE
E
C
D
SW
φ_1
f_1
f_2
B
1



S
E
B
N
50
25
0 m
φ_1
f_2
f_1
2

fig. 33

Top: Location of outcrops near C. Piangennaro.

Bottom: 1) Cross-section through localities B, C and D.

2) Cross-section through B and E.

Short outcrop descriptions:

A) Homogenous grey marls overlying a sandstone-marl alternation with attitude 275-45 N. Location of sample a), (See appendix, 8).

B) Tectonized sandstone-shale alternation of the CSC situated 10 m downstream a small waterfall over a cliff of San Salvatore Sandstone.

C, D) Deserted quarries in thick bedded San Salvatore Sandstone. Bed attitude 292-22 N. Minor fault with 240-80 NW (f_2) in C.

E) Sheared, boudinaged and small-scale folded San Salvatore Sandstone. Attitude appr. 290-20 N overturned; cleavage subparallel to bedding; joints at 235-75 NW.

F) Tectonized calcare e argilla outcrops of the CSC.

fig. 34

Equal area projections in upper hemisphere. Numbers represent the percentage of the amount of observations (top right between brackets) in 1 % of the area.

a) poles to bedding in San Salvatore Sandstone and Brugnello Shale.
o means: between 0 and 0.5 %.
There is no axial dip. The large recumbent syncline and the footwall syncline have an equal vergence.

b) poles to joints in all Oligo-Miocene rocks of the window.

c) poles to joints in San Salvatore Sandstone and Brugnello Shale.

d) poles to joints in Ruffinati Siltstone and Aveto Sandstone.

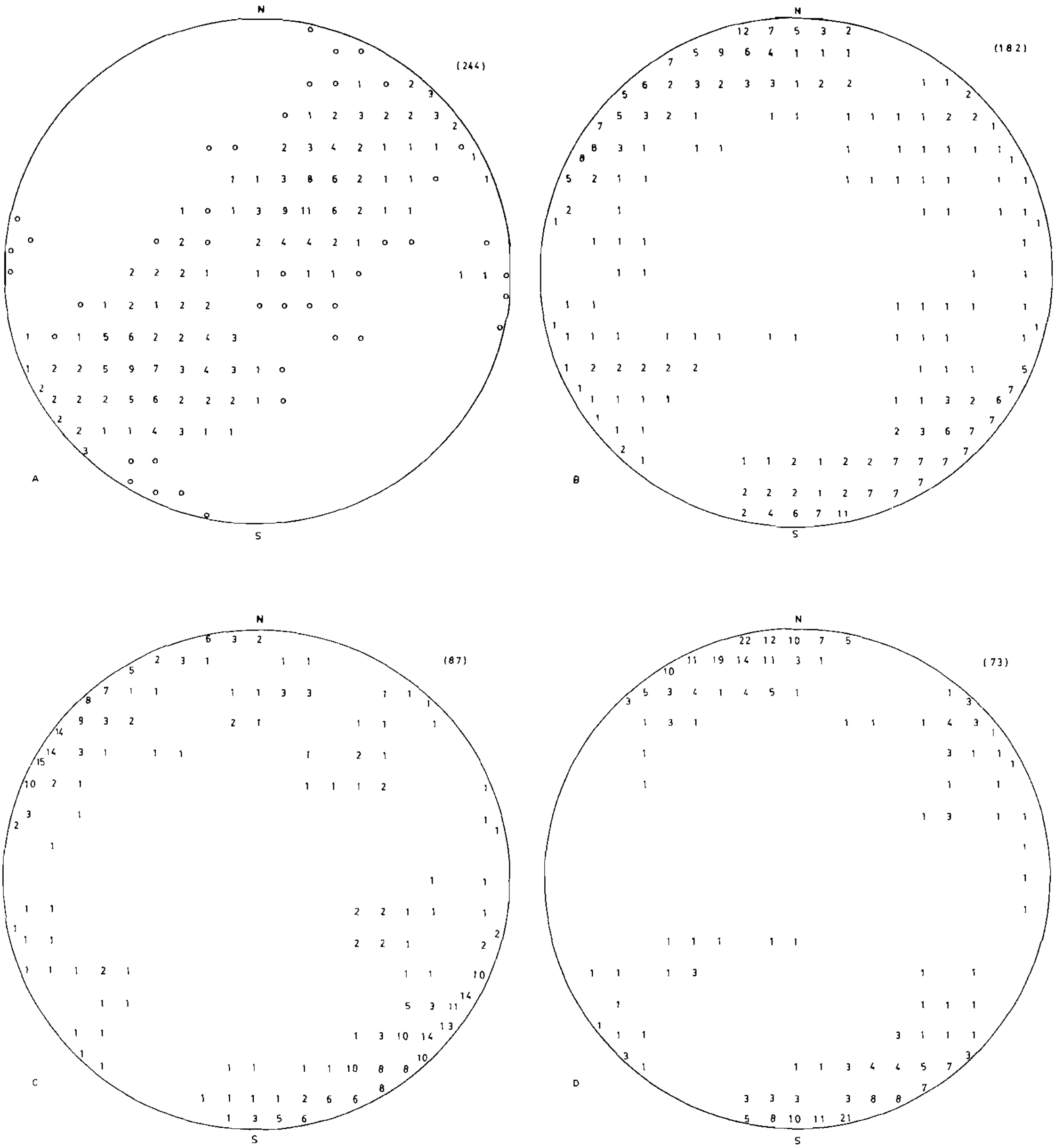


fig. 34 Explanation on p. 87.

38 Joints

We have measured attitudes of joints in the Oligo-Miocene rocks of the window. The strikes generally coincide with the transversal direction, and they dip 75 - 90^{o}. Their orientation, perpendicular to the Apenninis trend, is not surprising (fig. 34^{b}).

The meaning of the small angle in joint orientations in the Aveto-Ruffinati sequence and in the Tuscan sequence is not clear (fig. 34$^{c,\ d}$): this angle is not evident in bed orientations.

39 The relationships of the tectonic units

The superposition of the various tectonic units in the Trebbia valley leads to the following conlcusions:

- The CSC overthrust (ϕ_1)

  The CSC is of internal origin with respect to the San Salvatore Sandstone. This is demonstrated by the orientation of the drag structures near the thrust plane, e.g. the footwall syncline (section 25). The strongly NE-vergent recumbent syncline in the Tuscan unit is possibly a product of the CSC overthrust as well.

  The slip of the thrust is at least 7 km, as measured between Marsaglia and Barberino. The blocks of Tuscan sandstone found at the SW outcrops of the CSC thrust plane must have originated from a more internal part of the Tuscan nappe now covered by other units.
- The Ruffinati-Aveto thrust (ϕ_2)

  We do not dispose of age data of the Ruffinati Siltstone but the fair similarity with the CSC leads us to suppose that these two formations belonged to roughly the same sedimentary basin. This implies that the slip of the Ruffinati thrust need not be large. Geometrical control is lacking.

- The M. Penice overthrust (ϕ_3)
  This thrust truncated the Ruffinati-Aveto thrust. The olistostromes in the Ruffinati-CSC basin are precursory to the M. Penice emplacement as indicated by their components.
  The minimum horizontal displacement of the M. Penice thrust amounts to some tens of kilometers: the window is 20 km wide at this level.
- The Ligurid thrust (ϕ_4)
  The Ligurid is the largest one. Ligurid outcrops occur from the Ligurian Sea to the Po Plain (fig. 35). Semi-allochthonous rocks on top of the Ligurids have moved 35 km in NNE direction according to Vezzani and Passega (in: Sestini, 1970). This figure is exceeded by the minimum distance measured from the most southern part of the window of Bobbio to the Padan margin (40 km).

The emplacement of all thrust sheets took place in post-Aquitanian Miocene times. Early Pliocene movements of the Ligurids at the Padan margin have been reported by Lucchetti et al. (1962).

IV CONSIDERATIONS ON REGIONAL TECTONICS

40 Introduction

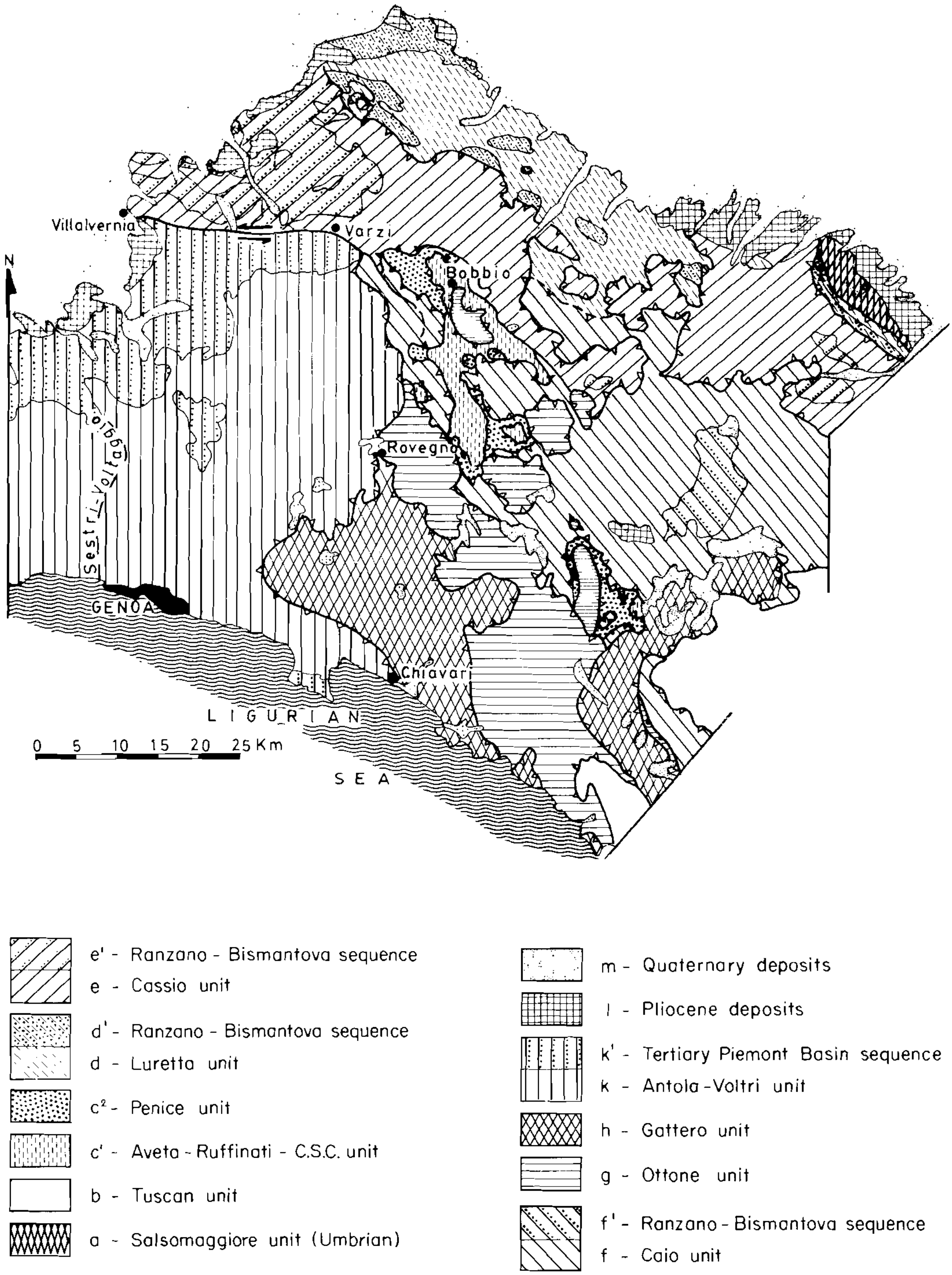
The overthrusting of internal units over more external units has generally been accepted in Apenninic geology and is demonstrated by tectonic onlap over progressively younger units towards the NE. The paleogeographic reconstructions derived from this model are satisfying, though, rather rough. The main problem is a space problem: the width of the overthrust units (Tuscanids and Ligurids) exceeds the extent of the present Tyrrhenian Sea. The width of the flysch basins in the Late Cretaceous was 250 km according to Sagri (1973). The author gives the following figures:

Antola	230 x 80	18.400 km^2	24.840 km^3
Cassio	220 x 30	6.600	9.900
M. Venere	120 x 35	4.200	2.100
Gottero	90 x 40	3.600	3.960
Pietraforte	200 x 40	6.800	6.800
		40.000 km^2	47.600 km^3

The minimal horizontal NE translation of the overthrust units in the Trebbia valley is (section 39):

Coli-Sanguineto overthrust : 7 km
Ruffinati-Aveto overthrust : ?
M. Penice overthrust : 20 km
joint Ligurid overthrust : 40 km. This figure applies to the Ligurids in the investigated area only. The slip of the overturned Ottone unit and of the Gottero unit is not known, but it would presumably add at least 25 km (fig. 35).

The total translation is at least 70 km, as the internal shortening of the nappes by folding, reverse faulting and overturning have not been considered (fig. 35).



Villalvernia
Varzi
Bobbio
Rovegno
Sestri-Voltaggio
GENOA
Chiavari
LIGURIAN
SEA
N
0 5 10 15 20 25 Km
e' - Ranzano - Bismantova sequence
e - Cassio unit
d' - Ranzano - Bismantova sequence
d - Luretta unit
c² - Penice unit
c' - Aveta - Ruffinati - C.S.C. unit
b - Tuscan unit
a - Salsomaggiore unit (Umbrian)
m - Quaternary deposits
l - Pliocene deposits
k' - Tertiary Piemont Basin sequence
k - Antola - Voltri unit
h - Gattero unit
g - Ottone unit
f' - Ranzano - Bismantova sequence
f - Caio unit

fig. 35 Tectonic map delineating the probable tectonic units and sub-units of the Ligurid Complex (after Sestini, 1970; Carta Geologica d'Italia, sheets 71, 72, 83; Venzo, 1966).
The Ronco Sandstone and the Montoggio Shale have been tentatively included in the Antola-Voltri unit.

This distance has been covered in Miocene times.

On the other hand, the Antola-Voltri-Piemont block would have been an obstacle to the NE-ward movement of the Ligurid sheets unless this block would originally have been situated more to the W with respect to the Apennines. We speak of the Antola-Voltri-Piemont block because the Tertiary Piemont Basin series overlies the Antola Limestone and the Voltri Group and welds these units together; from early Oligocene times on the Sestri-Voltaggio zone is a fossil line (fig. 6).

The actual outcrop pattern of the Ligurid units implies that the A-V-P block should have been situated at least 50 km to the W in order to make way to the Miocene Ligurid thrusts. In this respect we not even consider the, probably allochthonous, position of the Tuscan core of the window of Bobbio.

If the Ligurids of the Monferrato (W of Turin) also underwent a Miocene translation to the NE, the A-V-P block would have been situated even more westerly.

Thus it appears that the A-V-P block and the true Apenninic units were quite independent. If so, we must indicate the limit of such independent structures. We aim to demonstrate a) that the Varzi-Villalvernia lineament is a sinistral strike-slip fault which separates the A-V-P block from Apenninic units and b) that the eastern extremity of the lineament bends south near Varzi and passes into an overthrust of the Antola Limestone over a Ligurid footwall.

41 The Varzi-Villalvernia lineament

The Antola slab is definitely the largest continuous outcrop of Helminthoid flysch in the Northern Apennines. It covers the area surrounded by the Sestri-Voltaggio line, the Ligurian coast from Genoa to Chiàvari, the Lavagna-, Trebbia- and Staffora valleys and the Tertiary Piemont Basin series that overlies its northern and northwestern parts. The latter is limited by a fault that runs westward from Varzi to Villalvernia. Beyond, it is buried by Pliocene sediments of the Asti Basin.

The Varzi-Villalvernia line divides two geologically different areas: the coherent Antola compartment to the S and the Cassio compartment to the N. Though the lithologies in both compartments are related and, in general lines, parallel, the Cassio compartment is formed by a complicated geological patchwork (Çarta Geologica, F. 71).
The Tertiary sequence which overlies the Helminthoid flysches differs on either side of the Varzi-Villalvernia lineament: the conglomerates are not coeval and their compositions are distinct; correlation of the tectonic phases in both compartments does not seem possible; the Oligocene sequence of the northern compartment is totally different from that of the southern compartment; chaotic shales, frequently intercalated in the Miocene sequence of the northern compartment, lack in the south (oral comm. Dr. J.W. Zachariasse).

The Varzi-Villalvernia lineament is unstable up to recent times: nearly annually weak shocks are reported in the area.

42 The Antola Limestone vs. the Monte Cassio Formation

Both Antola- and M. Cassio formations represent the Upper Cretaceous Helminthoid flysch, a widespread facies in the Apennines, the Swiss Alps and the Western Alps.

However, difficult to establish in small exposures, according to Abbate and Sagri (1970) the two formations differ in that the M. Cassio Formation has a significantly higher shale- and marlstone content than the Antola Limestone.

The Antola- and M. Cassio formations are overlain by the Albirola Formation (= Argilliti di Pagliaro) and the Viano Clays respectively (Carta Geologica, F. 71). They differ by the presence of obvious megarhythms in the Albirola Formation. Both formations are assumed to be of Paleocene age.

The Monte Cassio Formation is underlain by variegated shales and the Scabiazza Sandstone. The Salti del Diavolo Conglomerates are intercalated in the latter. The provenance area of the pebbles is probably southern Alpine (Sames, 1967). Possibly they even originate from the Lago Maggiore area (Giammetti, 1966).

There is no certainty about the stratigraphic base of the Antola Limestone. It is underlain by variegated shales, commonly referred to as Montoggio Shale and, probably, by an argillaceous complex with sandstone bodies (Ronco Sandstone) (Carta Geologica, F. 83). We think that this sequence overlies the Ligurid Complex tectonically: in an internal report, Dijksman (1970) showed the following features at this contact:

- overturned beds of Antola Limestone on top of variegated shales near Ponti;
- normally lying Antola beds overlying overturned Scisti Galestrini;
- the strongly changing character of the rocks interposed between the Antola Limestone and the Scisti Galestrini;
- folds in the Antola Limestone and the Scisti Galestrini, both with easterly vergences;
- excessively strong deformation of the Montoggio Shale in outcrops in the T. Avagnone bed 1200 m N of the Trebbia-Avagnone confluence.

43 The eastward continuation of the Varzi-Villalvernia lineament

In this section we will discuss the concept that the transcurrent Varzi-Villalvernia lineament passes into an eastwardly directed overthrust of the Antola slab over Ligurid units. We already mentioned the structural disharmony between the Antola Limestone and the Scisti Galestrini between Varzi and Rovegno. More to the S, in the Lavagna valley, the Antola front is necessarily located between the outcrops of the Antola Limestone and the practically coeval Gottero Sandstone (= Arenarie Superiori), two entirely distinct formations by their lithology.

The Antola front disappears in the Ligurian Sea near Chiàvari. The lithologic units E of the Antola slab are considered to belong to the most internal domains of the Apenninic sedimentary basin. They include "palombino" limestone, calpionellid limestone, chert, shales and ophiolites. These Ligurids form a complicated pile of thrust sheets, which are hard to delineate. An attempt has been made in fig. 35.

The emplacement of the Antola slab in its present position occurred after the formation of the pile of Apenninic thrust sheets and consequently happened in a very late stage in the regional diastrophism. Indeed, Lower Pliocene deposits have been offset by the Varzi-Villalvernia lineament near Villalvernia (internal report by Drs. E. Thomas).

Some observations support this hypothesis:

- The Ligurids between the Staffora River and the window of Bobbio have been doubled locally;
- The Canetolo- and Ligurid thrust planes have been tilted W, especially where situated close to the Antola front; e.g. in the Traschio window near Ottone the thrust planes dip 45° W;

- The San Salvatore strike-slip fault cutting through the window of Bobbio is a sinistral one, which is concurrent with the stress field that is to be expected in case of relative eastward motion of the Antola slab.

44 Review of the regional diastrophism

The Apenninic units

For the development during the Cretaceous we refer to various authors (Elter et al., 1966; Gelati and Pasquaré, 1970; Abbate and Sagri, 1970; Haccard et al., 1972). In the Late Cretaceous the Ligurid basin became divided into an external and an internal part by the rise of the Bracco Ridge of which the backbone consisted of oceanic crustal material.
During the Paleocene, sedimentation continued in the external basins and, even more externally, in the Canetolo domain. The Bracco ridge developed into a thrust sheet that partly overrode the external Ligurids.
In the Eocene the sedimentation of the Tertiary calcareous flysches in the Canetolo domain was interrupted by the Ligurian phase. It affected Ligurid and Subligurid (= Canetolo) rocks. After this phase the Ligurid sequences were unconformably covered by the clastic Ranzano-Bismantova sequence. Subligurid sedimentation continued up to Early Miocene times in progressively more external parts.

To explain the now vanished area the Ligurid basin has once occupied, a great amount of crustal shortening is necessary. There are indications for andesitic volcanism during the late Paleogene, suggesting crustal shortening by subduction. Andesitic tuffites and cinerites are observed in Oligocene and Miocene sediments at various places in the Northern Apennines and in the Swiss and Western Alps (Elter et al., 1969; Aiello, 1975; Wezel, 1977). Possibly, also fragments of Hercynian crust have been uplifted in the Canetolo domain.

During the Miocene, important horizontal translations caused the actual nappe structure. The Tuscan series was doubled and overthrust by units of progressively more internal origin:

- Oligo-Miocene parts of the Canetolo Complex,
- Paleogene parts of the Canetolo Complex,
- the Ligurid Complex, composed of several sub-units. Of those, the arkosic Gottero Sandstone occupied an internal position relative to the Bracco Ridge, as it overlies the main belt of ophiolite masses arranged along the so-called Varzi-Ottone-Levanto lineament.

The final horizontal movements are recorded along the Padan margin during the earliest Pliocene. Subsequent block-faulting and gentle folding also started in Pliocene times.

The Antola-Voltri-Piemont block

In section 40 we explained that in Late Cretaceous times a large area separates the A-V-P block from the Apenninic realm. In Eocene times the Sestri-Voltaggio lineament has been the site of compression and of sinistral strike-slip movements (Debelmas, 1975; Haccard et al., 1972; Elter and Pertusati, 1973; Chiesa et al., 1975). It is even presumed to be the eastward prolongation of the North Pyrenean Fault (Debelmas). In the Oligocene the area was invaded by clastic sediments (Tertiary Piemont Basin series).

The Apenninic and the A-V-P blocks approached each other throughout the Paleogene. The A-V-P block reached its actual position after the thrusting of the Ligurids over their foreland. Its northern limit is the Varzi-Villalvernia lineament, its eastern limit is the Antola front. The last impact is recorded by reverse- and transcurrent faulting and westward tilting of the Apenninic thrust planes.

The Antola-Voltri-Piemont block is probably a shallow structure. Geophysical data do not suggest a fault zone in the basement; Haccard (in Debelmas, 1975) stated that the Voltri Massif is allochthonous and limited downward at 800 - 1000 m, affirming that the A-V-P block is a superficial slab.
The horizontal slip of the Varzi-Villalvernia line is at least equal to its outcropping length of 20 km. Spatial considerations, as discussed above, suggest much more.

V CONCLUSIONS

- In the multiple window of Bobbio the following tectonic units are superimposed over the Tuscan unit:
  - Ligurid Complex
  - M. Penice unit
  - Ruffinati-Aveto unit
  - Coli-Sanguineto Complex
- The Tuscan unit is a recumbent syncline with a strong NE vergence.
- The Coli Complex and the Suiguineto Complex, mapped by Bellinzona et al. (1968), are identical. This is confirmed by their lithology and by paleontological data. The two complexes should be united, stratigraphically and tectonically, in a single Coli-Sanguineto Complex, that has overridden the Tuscan unit. The latter divides the CSC outcrops into a northern and a southern area.
- The Northern part of the CSC thrust plane is lined by the so-called "Peli Argillites". They are not a stratigraphic entity but a tectonic mixture of units adjacent to the thrust plane.

  A footwall syncline has been formed along the NW part of the CSC thrust.
- The Ruffinati Siltstone passes into the Aveto Sandstone by a disturbed stratigraphic contact. The Ruffinati-Aveto unit is separated from the CSC by a tectonic contact, which is truncated by the M. Penice overthrust.
- The "calcare e argilla" olistostromes in the CSC and the Ruffinati Siltstone are derived from the M. Penice sequence. Admixture of Ligurid rock types has been reported by Labesse and Magné (1963). The olistostromes are abundant in the CSC but they are only subordinate in the Ruffinati Siltstone.

- The Aveto Sandstone lacks "calcare e argilla" olistostromes; the conglomerates of the Aveto Sandstone are different olistostrome deposits. Their components indicate a source area with granitic, ophiolitic, metamorphic and sedimentary rocks. The granitic and metamorphic clasts may have been derived from Hercynian crustal remnants.
  The green andesitic tuffites of the Aveto Sandstone might be related to a subduction zone.
- The Coli-Sanguineto Complex, the Ruffinati-Aveto sequence and the M. Penice unit all are sub-units of the Canetolo Complex, defined as the rocks interposed between the Ligurids and the Tuscanids.
- Overthrusting of the window of Bobbio started not before Early Miocene. The Ligurid overthrust is the youngest one. It reaches as far as the Padan margin where it is reported to overlie Miocene deposits by drillings (Lucchetti et al., 1962).
- The Antola-Voltri complex is allochthonous. The Tertiary Piemont Basin series is its semi-allochthonous cover. The Antola slab is bordered in the N by the Varzi-Villalvernia lineament, a sinistral strike-slip fault, and in the E by a W-dipping thrust plane at the level of the Montoggio Shale. It has been emplaced after the completion of the entire Apenninic pile of thrust sheets.

APPENDIX

1) Labesse and Magné (1963):

Faunal contents of the Macigno:

terme inferieur: *Globorotalia cf. opima-G.cf.mayeri-Globoquadrina sp.* - benthonic forms.

terme supérieur: *Globigerina venezuelana-G.ampliapertura-G.rohri-Globorotalia cf.opima nan-G.cf.mayeri-Globorotaloides suteri.*

2) Boni et al. (1968):

Faunal contents of the Argilliti di Brugnello (point 961):

Globoquadrina dehiscens-Globigerinoides trilobus-Globorotalia mayeri-Globigerina venezuelana.

dehiscens is reported to be abundant. Inferred age: Langhiano.

See also section 12 of the present work.

3) Pannella and Pizzocchero (1962):

Faunal contents of the sandy-marly facies of the CSC.

both the Peli-Averardi and the Rio Assalto sections:

Globigerina bulloides-G.dissimilis-G.venezuelana-Globigerinoides trilobus-Globoquadrina quadraria-G.dehiscens-Globorotalia opima nana-G.mayeri.

only at Peli-Averardi: *Globigerina ampliapertura.*

only at Rio Assalto: *Globoquadrina cf.larmeui-G.cf.obesa.*

4) Fauna of "Argile de Bobbio", proprement dite:

Globigerina (Catapsydrax) dissimilis-G.ampliapertura-G. venezuelana-Globorotalia opima- many benthonic forms.

Age: "undoubtedly Oligocene at all levels of the formation".

5) Mutti (1963):

"argilla" near Bernazzani and Rio Rondinera:

Catapsydrax dissimilis-Globigerina ampliapertura-G.venezuelana-Globorotalia opima- many benthonic forms.

Age: Early Oligocene.

6) Mutti (1964):

"argilla" lens at the Confiente bifurcation:

Cataspydrax dissimilis, Globigerina venezuelana, G.yeguaensis. Globorotalia centralis, G.sp.,Globorotaloides (?) suteri.

Inferred age: M. Eocene.

7) Mutti (1964):

Curiasca valley N of Peli:

Globigerina cf.venezuelana-Globigerinoides triloba-Globoquadrina dehiscens-Globorotalia mayeri-G.opima-G-scitula- benthonic forms.

Age: Late Oligocene-Aquitanian.

8) Present report:

The determinations have been carried out by Dr. J.W. Zachariasse of the Utrecht Micropaleontological Department. The identification of the foraminifera is extremely difficult and precise zone assignment of the faunas is not possible.

a) This sample has been taken from a marl overlying the sandstone-marl alternation at the right bank of the Trebbia opposite Bobbio (NQ $313^{3}572^{8}$):

Globoquadrina venezuelana

Catapsydrax spp.

Neogloboquadrina opima opima

The presence of *N.opima* s.s. points to a correlation with Bolli's *G.opima* Zone (= lower part of Blow's N2).

Age determination: Late Oligocene.

b) Taken from the upper portion of the marls in the Magrini section, (NQ $336^{8}543^{3}$).

Neogloboquadrina siakensis

Globigerinoides trilogus

Catapsydrax spp.

Globigerina woodi

Globoquadrina cf. dehiscens

Age determination: Early Miocene (Aquitanian-Burdigalian)

c) Sampling locality: homogenous marls exposure at the bifurcation of S.S. 45 near Confiente (NQ $294^{3}501^{0}$).

Globoquadrina venezuelana

G. cf. tripartita

Catapsydrax sp.

Neogloboquadrina cf. opima nana

Globigerina praebulloides

G. suteri

G. woodi

The presence of *G. woodi* would indicate a Late Oligocene age.

d) Sampled at the southern end of the village of Telecchio (NQ $322^{2}528^{2}$).

Neogloboquadrina siakensis

Globigerina woodi

Catapsydrax dissimilis

Globigerinita glutinata

Globoquadrina dehiscens

Globigerinoides trilobus

This is a Lower Miocene association (N4 - N6; Aquitanian-Burdigalian)

e) Sampled in marls at location NQ $326^{6}530^{2}$ 500 m E of Telecchio.

Neogloboquadrina siakensis

Globogerinita cf. quinqueloba (possibly accompanied by forms belonging to the *Globigerina ciperoensis* group)

Globigerinoides cf. primordius

G. trilobus group

Globigerina woodi

Globigerinita glutinata

Age determination: Early Miocene (Aquitanian-Burdigalian)

f) **Sample from grey marls near km 2 of S.S. 586. (NQ 297^{3}498^3).**

Globoquadrina tripartita

G. venezuelana

Globigerina cf. ampliapertura

Neogloboquadrina opima nana

N. cf. opima opima

Age: Late Oligocene.

Calcareous nannoplankton (determinations by Drs. A.J.T. Romein, Utrecht Micropaleontological Department):

Reticulo scissura

Coccolithus cf. eopelagicus

Sphenolithes moriformis

S. distentus

Age determination: Middle or Late Oligocene.

9) **Labesse and Magné (1963):**

Faunal contents of "Argile de Bobbio", sédiments remaniés:
Alveolina sp.-Nummulites sp.-Operculina sp.-Discocyclina marthoe-Actinocyclina sp.-Asterodiscus sp.-Asterigerina sp.-Sphaerogypsynoides sp.-Fabiana sp.-Rupertia sp.-Rotalia sp.- **etc.**

The fauna is comparable to that of the M. Penice Limestone.

Pebbles with: *Calpionella undelloides-Stomiosphaera minutissima.*

Marls with: *Globigerina yeguaensis-Truncorotalia gr.crassata-Globoratalia spinulosa-G.cf.centralis.*

Globigerina linaperta-G.cf.boweri-Globigerapsis cf.kugleri-Globorotalia cf.centralis-G.cf.spinulo-inflata-Truncorotaloides sp.-Globigerina linaperta-G.yeguaensis-Globigerina sp.

Inferred age of the marls: Lutetian.

10) **Schlüter (1968):**

Graumergel-Serie:

Globigerina ampliapertura, G.cf.dissimilis, G.tripartita.

Inferred age: Late Eocene-Oligocene.

11) Labesse and Magné (1963):

Faunal content of the M. Penice Limestone:

Globigerina yeguaensis, G.linaperta, G.dissimilis, G.aff. senni, Globigerinoides orbiformis, G.cf.index, Globigerapsis cf.kugleri, Globorotalia centralis, G. bullbrooki, G. spinulosa, G.cf.spinulo-inflata, G.cf.lehneri, G.aff.crater, Truncorotaloides cf.rohri.

Age: Lutetian.

12) Aiello (1975): "The Petrignacola Sandstones are mainly composed of andesitic clasts with a holocrystalline, hypocrystalline or in part glassy groundmass with a pilotaxic or intersertal structure. The phenocrysts are zoned plagioclases with sharp contours, amphiboles and subordinate pyroxenes. The plagioclases have an andesitic to labradoritic composition and may be altered to albite, chlorite, sericite and epidote. The groundmass of the andesitic clasts is sometimes intensely chloritized. Apart from andesitic fragments, metamorphic and sedimentary particles and undulose quartz are present.

The Aveto Sandstones presents nearly identical characteristics; the percentage of andesitic fragments is slightly lower and the amount of plagioclase is relatively higher".

13) Boni et al. (1968):

Thin sections of conglomerate pebbles of the Aveto Sandstone:

Globoquadrina sp., Globigerinoides cf. irregularis, G. trilobus, Orbulina universa.

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Nawoord

Tot slot richt ik gaarne een woord van dank aan allen die hebben bijgedragen tot mijn geologische vorming en de totstandkoming van dit proefschrift.
In het bijzonder ben ik dank verschuldigd aan:

Mijn promotor, Dr. E. ten Haaf, die mij met zachte overreding op het goede spoor hield. Hij hielp me bij het onderscheiden van problemen van schijn-problemen; zijn ervaring en zijn vernuft waren voor mij onmisbaar.

Dr. W.A. van Wamel, wiens belangstelling voor mijn werk leidde tot dikwijls uitvoerige gedachtenwisselingen.

Dr. J.W. Zachariasse en Dr. A.J.T. Romein, ik deelde jullie vertwijfeling over de vaak erbarmelijke kwaliteit van het monstermateriaal waarmee ik jullie lastig heb moeten vallen.

Aan de samenwerking met mijn collega's en vrienden Jan, Joop en Manfred heb ik veel genoegen beleefd. De afstand tussen scherpe kritiek en ontspanning werd door jullie met een haast speelse vanzelfsprekendheid overbrugd.

Beste Carla, zonder jouw vele correcties was mijn Engels wellicht alleen voor Nederlanders begrijpelijk geweest.

Beste Wilma, enorm bedankt voor je nauwgezette typewerk.

De medewerkers van de foto- en tekenkamers o.l.v. de heer F. Henzen, hebben mij, steeds op sympatieke wijze, met raad en daad bijgestaan.

Vorrei ringraziare i geologi dell'Instituto Geologico dell' Università di Pavia per la loro cordiale accoglienza. Anche se le nostre interpretazioni discordino su qualque punto, la loro carta della finestra di Bobbio si è mostrato un lavoro preciso e di gran valore.

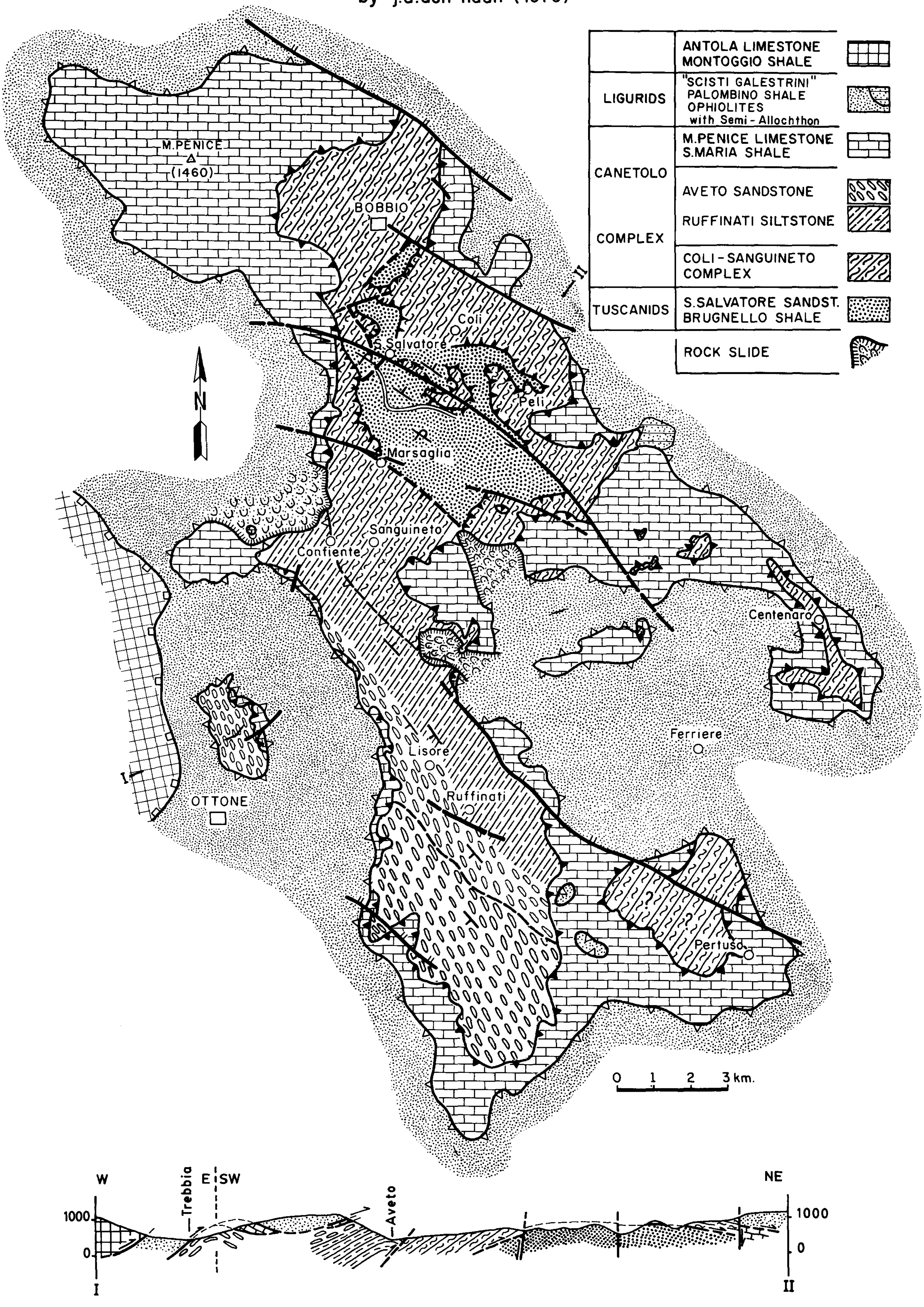
Sono molto riconoscente alle famiglie Carraro e Monfasani di Bobbio per la loro amicizia e ospitalità spontanea durante i miei frequenti soggiorni nella zona; anche gli abitanti di San Salvatore mi sono stati un gran aiuto nel mio lavoro. Sono molto contento di aver potuto conoscere in questa maniera la vita italiana e gli Italiani.

Curriculum vitae

De auteur van dit proefschrift behaalde in 1965 het einddiploma Gymnasium-B aan het Lorentz Lyceum te Eindhoven. Na gedeeltelijke vervulling van de dienstplicht werd in 1967 begonnen met de studie Geologie aan de Rijksuniversiteit te Utrecht. Het kandidaatsexamen G1 werd behaald in september 1970 en in juni 1975 volgde het doctoraalexamen structurele en toegepaste geologie met bijvakken sedimentologie en stratigrafie. Van juni 1975 tot juli 1979 was de schrijver werkzaam als wetenschappelijk medewerker bij de afdeling structurele geologie van voornoemde universiteit.

TECTONIC MAP OF THE WINDOW OF BOBBIO

by j.a.den haan (1979)



Erratum

p. 92: The explanation to fig. 34 is not on p. 87, but on p. 91.