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The structural geology and basin development of the Romagnan-Umbrian zone (Upper Savio- and Upper Bidente Valleys, N. Italy)

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Abstract

Combined stratigraphic and structural geologic studies in the region of the Upper Savio- and Upper Bidente Valleys lead to a re-interpretation of the Romagnan-Umbrian thrust zone, especially of the extent of the Castellaccio thrust unit. The Romagnan-Umbrian thrust zone may be characterized as a generally piggy back propagated, imbricate stack with a complex evolution.

The presence of a time equivalent turbidite marker bed (= 'Contessa Bed') within all thrust units enabled the balancing and restoration of the Romagnan-Umbrian thrust zone. The minimum amount of shortening of the 'Contessa Bed' appears to be about 48% of its original length. Folding accounted for about 49% and thrusting for about 51% of the total amount of shortening. The restoration indicates that, during the 'Contessa' event (dated as the Early Serravallian *Globorotalia peripheroronda* Zone = 14–14,5 Ma), the Romagnan-Umbrian turbidite basin had a minimum NE-SW width of 50 km.

After the 'Contessa' event, still during the Early Serravallian, an anticlinal culmination (= the San Paolo high) formed within the Romagnan-Umbrian turbidite basin, probably generated by blind thrusting during the Serravallian and Early Tortonian. On top of the anticlinal culmination a condensed section of clayey San Paolo Marls accumulated until the Middle Tortonian (9–10 Ma). The more calcareous Veghereto Marls have been deposited on the SW dipping limb of the San Paolo anticlinal culmination.

During the Middle Tortonian (9–10 Ma) sedimentation in the SW part of the Romagnan-Umbrian turbidite basin was abruptly terminated by the Ligurian overthrust. Simultaneously or shortly thereafter, the Romagnan-Umbrian sequences were also intensively folded and thrusted. The Romagnan-Umbrian thrust zone developed during this main deformation phase of the area.

After thrusting, a period of gentle folding, oblique-slip faulting and general uplift completed the structural geologic and sedimentary history of the studied region.

Introduction

The study area is situated in the external part of the Northern Apennines and is roughly centered on San Piero in Bagno, about 50 km SW of Rimini (Figs 1 and 2).

On stratigraphic and tectonic grounds, the rocks of the Northern Apennines are commonly divided into Ligurian, Tuscan and Romagnan-Umbrian units (e.g. Sestini, 1970; Squires, 1975; Dallan Nardi & Nardi, 1975; Reutter & Groscurth, 1978; Elter

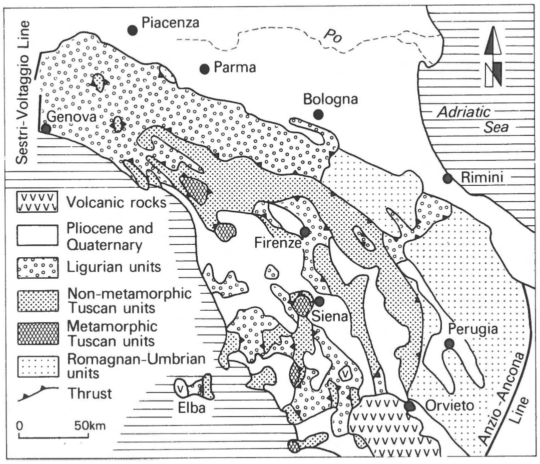

Fig. 1. Schematic tectonic map of the Northern Apennines. After Van Wamel et al. (1985).

& Scandone, 1980; Zanzucchi, 1980; Gruppo Appennino Settentrionale, 1982) (Fig. 1).

The internal Ligurian units contain oceanic rock assemblages of Late Jurassic – M. Eocene age (Abbate & Sagri, 1970; Elter, 1972; Van Wamel et al., 1985). Early NE directed thrusting of the Ligurian units took place during the Late Cretaceous to Eocene period and ultimately resulted in their positioning within the external ensialic domains (Van Wamel, 1987).

The external, Tuscan and Romagnan-Umbrian units are composed of rock assemblages, that were deposited in ensialic environments. Their Mesozoic base consists of Late Triassic evaporites, followed by platform carbonates and pelagic siliceous carbonates. The Tertiary parts of the Tuscan and Romagnan-Umbrian units are dominantly composed of clastic wedges with hemi-pelagic pelites at their base and top (see De Feyter et al., 1990, this issue). The pelites and clastic wedges of both the Tuscan and Romagnan-Umbrian units are strongly diachronous and they accumulated, according to Ricci Lucchi & Ori (1985), in NW-SE oriented, elongated basins in front of the Northern Apenninic fold- and thrust belt. The basins were dominantly filled with turbidites and were subsequently incorporated into the deformed belt, which from the Oligocene migrated in NE direction, towards the Adriatic 'Foreland' (see also De Feyter et al., 1990, this issue).

One of the main purposes of the present study is the reconstruction of the Romagnan-Umbrian turbidite basin in the region of the Upper Savio and Upper Bidente Valleys (Fig. 2). This area has been thoroughly investigated during the last three decades. Regional geologic studies have been executed by Passerini (1958) and Frey (1969), whereas stratigraphic and sedimentologic investigations have been carried out especially by geologists of the University of Bologna; see e.g. Mutti & Ricci Lucchi (1972), Ricci Lucchi (1968, 1969, 1975, 1978, 1981), Ricci Lucchi & Ori (1985), Ricci Lucchi & Valmori (1980), Ricci Lucchi & Veggiano (1966). The structural geology was described by Ten Haaf & Van Wamel (1979).

In the southernmost part of the area the Modino-Cervarola unit (also called Falterona Nappe) is exposed. It is the most external thrust unit of the Tuscan complex and it is tectonically superimposed over the Romagnan-Umbrian complex (see Fig. 2). Immediately SW off the study area the Modino-Cervarola thrust unit is thrust over by the Ligurian complex. According to Boccaletti et al. (1987) the Ligurian thrust over the hemi-pelagic top sequence of the Modino-Cervarola unit (= Vicchio Marls) during the Serravallian. The footwall of the Tuscan front contains the thrust units of the Romagnan-Umbrian complex. Based on their relative tectonic position, Ten Haaf & Van Wamel (1979) distinguished three tectonic zones within the Romagnan-Umbrian complex. From NE to SW these are: 1) the Romagnan 'Autochton', 2) the Romagnan Parautochton and 3) the Ultra-Romagnan, the latter divided into a lower Castellaccio (NE) and an upper Nero (SW) thrust unit. In the central part of the study area Ligurian material is found thrust over part of the Romagnan-Umbrian thrust zone.

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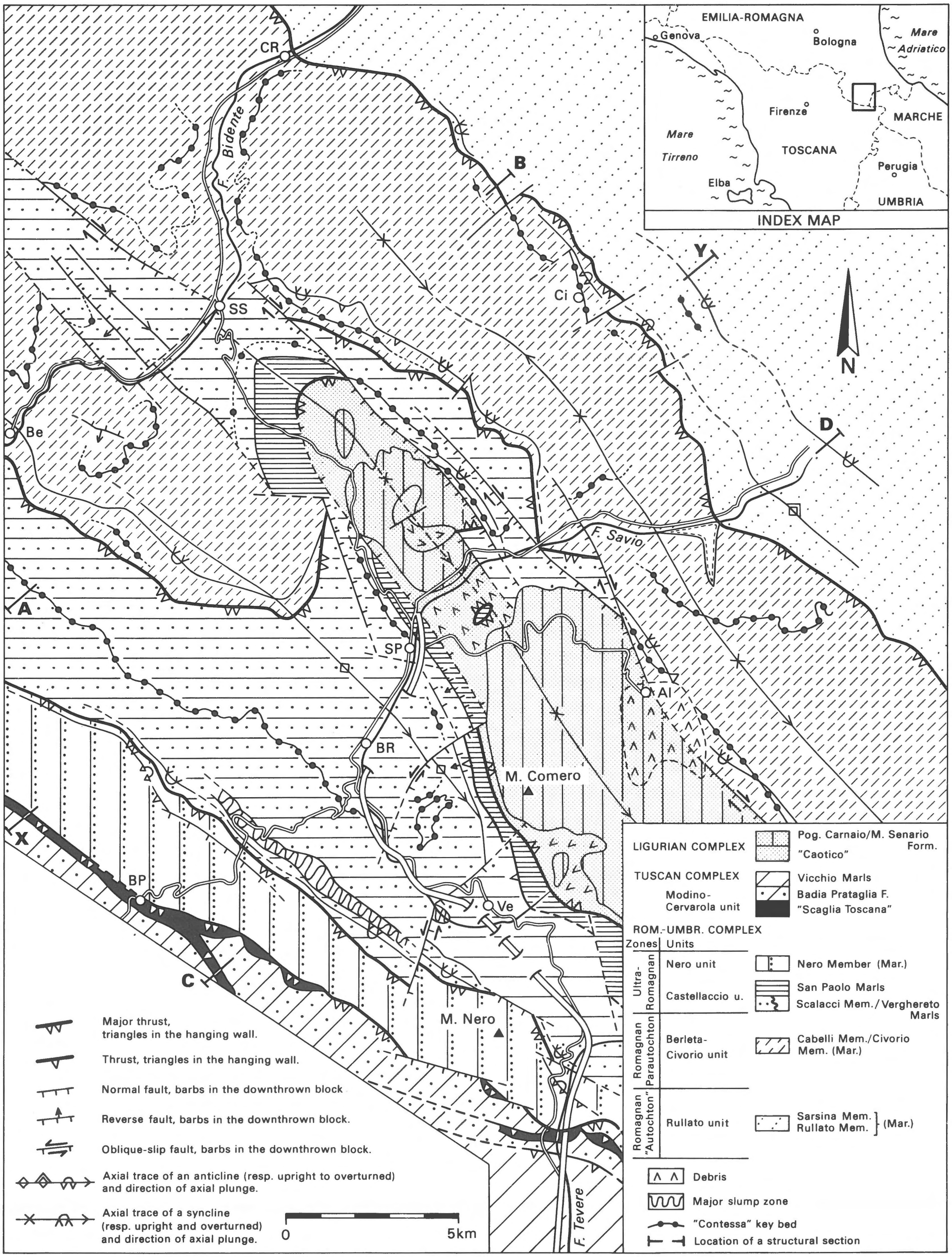
Fig. 2. Structural geologic map from the region of the Upper Savio and Upper Bidente Valleys. Abbreviations: Al = Alfero, Be = Berleta, BP = Badia Prataglia, BR = Bagno di Romagna, Ci = Civorio, CR = Civitella di Romagna, SP = San Piero in Bagno, SS = Santa Sofia, Ve = Verghereto. Cross sections A–B and C–D shown in Fig. 4 and cross section X–Y in Fig. 5, respectively.


EMILIA-ROMAGNA
Genova
Bologna
Mare Adriatico
Firenze
MARCHE
Mare Tirreno
TOSCANA
Perugia
Elba
UMBRIA
INDEX MAP
CR
F. Bidente
B
Y
Ci
SS
N
Be
D
F. Savio
A
SP
Al
BR
M. Comero
X
BP
Ve
C
M. Nero
F. Tevere
0
5km
Major thrust, triangles in the hanging wall.
Thrust, triangles in the hanging wall.
Normal fault, barbs in the downthrown block
Reverse fault, barbs in the downthrown block.
Oblique-slip fault, barbs in the downthrown block.
Axial trace of an anticline (resp. upright to overturned) and direction of axial plunge.
Axial trace of a syncline (resp. upright and overturned) and direction of axial plunge.
LIGURIAN COMPLEX
Pog. Carnaio/M. Senario Form.
"Caotico"
TUSCAN COMPLEX
Modino-Cervarola unit
Vicchio Marls
Badia Prataglia F.
"Scaglia Toscana"
ROM.-UMBR. COMPLEX
Zones
Units
Ultra-Romagnan
Nero unit
Nero Member (Mar.)
Castellaccio u.
San Paolo Marls
Scalacci Mem./Verghereto Marls
Romagnan Parautochton
Berleta-Civorio unit
Cabelli Mem./Civorio Mem. (Mar.)
Romagnan "Autochton"
Rullato unit
Sarsina Mem.
Rullato Mem.
(Mar.)
Debris
Major slump zone
"Contessa" key bed
Location of a structural section

The stratigraphy and facies of the Romagnan-Umbrian sequences in the study area have been extensively described by Ricci Lucchi and his co-workers (see e.g. Ricci Lucchi, 1975). From that description, the sequences of all Romagnan-Umbrian tectonic zones appear to be composed mainly of basin plain turbidites of the Marnoso-arenacea Formation. Lateral transitions of the basin plain sequences into hemi-pelagic pelites, indicative for submarine highs and slopes, were established within the Castellaccio unit and the Romagnan Parautochton (sensu Ten Haaf & Van Wamel, 1979). As a major result these stratigraphic efforts established the existence of basin-wide turbiditic megalayers (e.g. the 'Contessa Bed'). Ricci Lucchi and his co-workers claimed that the 'Contessa Bed' had a basin-wide NW-SE extent of 150 km. This was highly questionable since their correlation of the 'Contessa Bed' was only based on lithostratigraphy. Moreover, the Bed appeared to occur in different thrust units.

As long as the amount of tectonic translation of these thrust units is unknown, the uniqueness of the 'Contessa Bed' as a statigraphic marker is merely an assumption. If, on the other hand, the 'Contessa Bed' represents indeed the result of one single basin–wide turbidity current, then the occurrence of this bed in all units of the Romagnan-Umbrian thrust zone offers a unique possibility to balance this zone and restore this part of the Romagnan-Umbrian turbidite basin.

Considering the foregoing, the purpose of the present study was defined as follows:

- To prove whether or not the 'Contessa Bed' of the study area was the result of one turbidity current within the Romagnan-Umbrian basin.
- If so, to use this bed to balance and restore the Romagnan-Umbrian thrust zone of the area and to reconstruct this part of the Romagnan-Umbrian turbidite basin.
- To combine stratigraphic and structural geologic investigations in order to analyse the sedimentary-tectonic history of the region.

Stratigraphy

Lithostratigraphy

Based on stratigraphic and tectonic evidence, we distinguish several tectonic complexes, zones and units in the area (see Figs 2 and 3).

Within the Ligurian complex no differentiation in tectonic units has been made. The base of the Ligurian complex is composed of 'Caotico', a chaotic melange of scaly clay with exotic components derived from Ligurian, Tuscan and Romagnan-Umbrian sequences. It is a tectonic melange that formed the detachment material of the Ligurian thrust. Within the 'Caotico' there are rigid blocks containing rock sequences with alternating quartz-arenitic turbidites and marls. These are the Poggio Carnaio and Monte Senario Formations (see Figs 2 and 3). The most external thrust unit of the Tuscan complex crops out in the southern part of the region, the Modino-Cervarola unit. Its basal formation contains variegated shales ('Scaglia Toscana') which served as detachment material to the basal thrust. Covering the 'Scaglia Toscana' one finds the Badia Prataglia Formation, an alternation of turbiditic greywackes, -quartz-arenites and marls. Lateral and vertical transitions of the Badia Prataglia Formation into both, the 'Scaglia Toscana' and the overlying Vicchio Marls have been found. Often, however, the contacts between the formations are tectonized. The Vicchio Marls are composed of an alternation of more or less calcareous and clayey marls containing some rare turbiditic quartz-arenites. These are basin slope deposits, most probably formed along the NE rim of the Modino-Cervarola turbidite basin.

For the Romagnan-Umbrian complex we adopted the zonation of Ten Haaf & Van Wamel (1979), differentiating it into the Romagnan 'Autochton', Romagnan Parautochton and Ultra-Romagnan zones. These zones are bounded by thrusts and within each zone the lithologic composition of the rocks is more or less constant but markedly different from other zones. Internal thrusting within the zones may lead to a further differentiation into tectonic units. With Ten Haaf & Van Wamel (1979), we divided the Ultra-Romagnan zone into

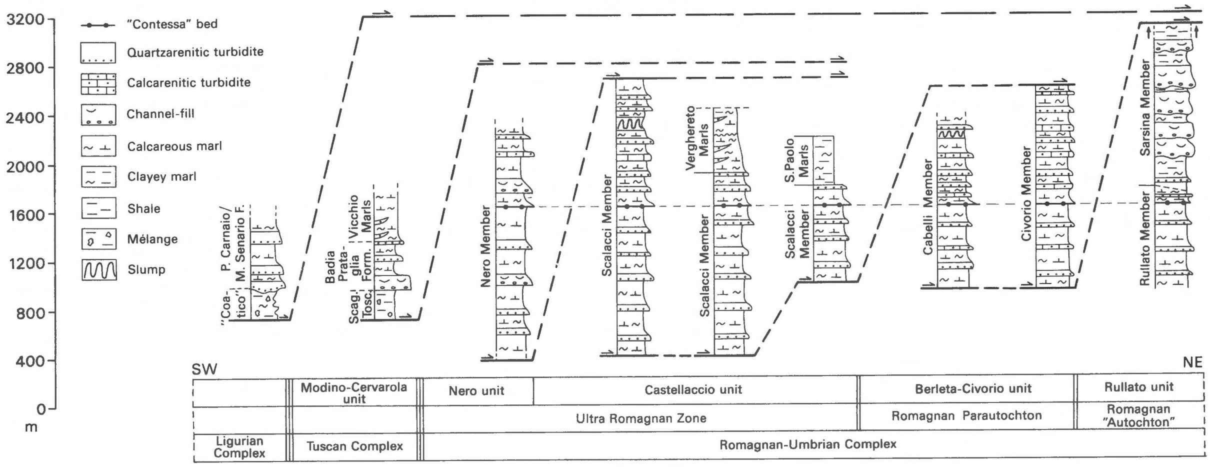


Fig. 3. Tectono-stratigraphic scheme from the region of the Upper Savio and Upper Bidente Valleys.

the Nero and Castellaccio units. The only thrust unit found in the Romagnan Parautochton zone of the region will be referred to as the Berleta-Civorio unit. Within the Romagnan 'Autochton' zone we distinguished only one tectonic unit, called the Rullato unit in this paper (see Figs 2 and 3). All arenaceous rock sequences from the Romagnan-Umbrian complex of the area were originally described as one lithostratigraphic unit, 'The Marnoso-arenacea Formation' (see e.g. Ricci Lucchi, 1975). To enable a proper description, we decided to subdivide this formation into members. From each tectonic unit the constituent members will be briefly described, in their order of superposition from below-upwards (see Fig. 3). In these description we used De Jager's (1979) purely descriptive classification of turbidite facies associations and his interpretations of their sedimentary environments.

The Rullato Member constitutes the lower part of Rullato unit. It is well exposed around the village of Rullato, situated directly E of Civorio to the NE-end of section X–Y (see Fig. 2). It is characterized by an alternation of quartz-arenitic turbidites and calcareous marls in facies association *e*, indicative of a basin plain environment. The lower boundary is not exposed, upwards the Rullato Member grades into the Sarsina Member, and its maximum thickness measured in outcrop is 800 m. The majority of the turbidites originated in the NW. Near Rullato a 'Contessa Bed' was found with a SE origin. Within the sequence directly covering the 'Contessa Bed' several calc-arenitic turbidites occur, also of SE origin. Approximately 100–150 m above the 'Contessa Bed' the transition into the Sarsina Member takes place near Rullato (Fig. 3).

The Sarsina Member is found in the upper part of the Rullato unit. It is well exposed in several road cuts and along rivers in the NE part of the area. It is characterized by an alternation of quartz-arenitic turbidites, marls and up to 10 metre thick quartz-arenitic debris flows. Within this member, vertical and lateral transitions occur between facies association *e* (basin plain) and facies association *a* (channel fill environment). The upper boundary of the Sarsina Member is not exposed in the area, the maximum thickness measured in outcrop is 600 m. Its thickness, reconstructed from section X–Y (Fig. 5a) is at least 1200 m. Northeast from the area the Sarsina Member grades into clayey marls of Tortonian age. The facies association *f* of these marls is indicative for a basin slope environment, that most probably developed along the NE rim of the Romagnan-Umbrian turbidite basin.

The Civorio Member constitutes the NE part of the Berleta-Civorio unit (see Figs 2 and 3). It is well exposed along the road cut SW of Civorio (Fig. 2). This member is characterized by an alternation of calcareous marls, quartz-arenitic turbidites and calc-arenitic turbidites in a facies association *e* (= basin plain environment).

The lower boundary is always tectonic, its upper boundary is tectonic or missing due to erosion. The estimated minimum thickness is 1550–1650 m. Nearly all quartz-arenitic turbidites have a NW origin of supply, except for a 'Contessa Bed', amongst others found near Civorio (Fig. 2), with a SE origin. This 'Contessa Bed' is situated at about 650 m above the basal thrust boundary of the member (Fig. 3). The regularly occurring calc-arenitic turbidites have a SE origin of supply.

The Cabelli Member constitutes the W part of the Berleta-Civorio unit (Figs 2 and 3). Except for some minor differences in the occurrence of calc-arenitic turbidites, which are less abundant in the Cabelli Member, the latter is quite comparable with the Civorio Member. Also in the Cabelli Member, a 'Contessa Bed' was established, at about 650 m above its supposed basal thrust boundary. At about 600 m above the 'Contessa Bed' we found the Rio Petroso slump zone, several tens of metres thick. The upper boundary of the Cabelli Member is tectonic or missing due to erosion. The estimated minimum thickness is 1300 m (Fig. 3).

The Scalacci Member is the lowermost stratigraphic unit of the Castellaccio tectonic unit and a magnificent section is exposed along the road between Bagno di Romagna and Badia Prataglia (see Fig. 3). This member is characterized by the alternation of quartz-arenitic turbidites and calcarous marls. Calc-arenitic turbidites are rare. Facies association *e* (basin plain) is predominant in the western part of the area, although lateral transitions occur into facies association *d* or *b* (= fan deposition within the deepest part of the basin). Most quartz-arenitic turbidites had a NW origin of supply except for a 'Contessa Bed' with a SE origin. The calc-arenites have a SE origin too. The lower boundary of the Scalacci Member is always tectonic. Vertical and lateral transitions have been established into the Verghereto Marls and the San Paolo Marls (see Figs 2 and 3). In the vicinity of the village of Verghereto the facies association *e* of the upper part of the Scalacci Member grades into the marly facies association *f*, most probably indicating the presence of an intrabasin slope. Around San Piero in Bagno (Fig. 2) the Scalacci Member with facies association *e*, *d* and/or *b* grades into the marly facies association *f* of the San Paolo Marls (see Figs 2 and 3). The estimated maximum thickness of the Scalacci Member is 2250 m. In the western part of the Castellaccio unit, within the Scalacci Member a 'Contessa Bed' was found at about 1200 m above the basal thrust (see Fig. 4, section A–B and Fig. 5a). Approximately 700 m above this 'Contessa Bed' there is a slump zone, the Casa Recetto slump zonc, at lcast 100 m thick (scc Figs 2 and 3). Structures within this zone indicate a SW direction of gliding. Where the Scalacci Member grades into the San Paolo Marls, a 'Contessa Bed' was found at 150–200 m below the lower boundary of the San Paolo Marls (Fig. 3).

The Verghereto Marls occur in the SE part of the Castellaccio unit (see Figs 2 and 3), where they are very well exposed and totally define the morphology of the area. The Verghereto Marls are composed for more than 90% of calcareous marls with some quartz-arenitic turbidite intercalations in the lateral transition zone with the Scalacci Member. The marly facies association *f* of the Verghereto Marls is indicative of an intrabasin slope environment, due to its lateral transition into the basin plain association *e* of the Scalacci Member. Originally, lateral and vertical transitions from the Verghereto Marls into the clayey San Paolo Marls may have occurred in a N to NE direction. At present these transitions are obscured, due to tectonisation of the original contact between the two marl formations (see Fig. 2). Within the Verghereto Marls there are several slump zones, which all give evidence of synsedimentary sliding in a SW direction, indicating a SW dip of the assumed intrabasin slope. Most boundaries of the Verghereto Marls are tectonized and therefore only a maximum thickness of 500 m can be estimated.

The San Paolo Marls constitute the highest formation of the Castellaccio unit, as distinguished in the present paper (see Figs 2 and 3). Formerly, Ten

Haaf & Van Wamel (1979) gave a different interpretation of the extent of the Castellaccio unit, whereby the San Paolo Marls were disignated to the Romagnan Parautochton zone. This formation is mainly composed of clayey marls that locally grade into more calcareous marls, both of facies association *f.* We find rare intercalations of thin quartz-arenitic turbidites in the basal part of the formation. There are strong indications for lateral and vertical transitions with both the Scalacci Member and the Verghereto Marls. Especially the transition into the Verghereto Marls, which are assumed to have been deposited on a intrabasin slope, and the occurrence within the San Paolo Marls of foraminifera that are indicative of a shallow marine environment (Zachariasse, 1989, pers. comm.) suggest that the San Paolo Marls accumulated on the upper part of an intrabasin high. The upper boundary of the San Paolo Marls is formed by the Ligurian thrust and therefore its thickness may be highly variable. Minimum estimates amount to 150–200 m, maxima to 400 m.

The Nero Member constitutes the Nero thrust unit and it is composed of an alternation of quartz-arenitic turbidites, greywacke-like turbidites and marls. The facies association *c* and the fact that turbidites with NW and SE paleocurrent directions are both present, may well indicate deposition within the realm of two fan systems. Characteristic of many turbidite beds is the presence of fossil remains in their basal parts. These turbidites may have had a more proximal origin, whereas the turbidites without such remains may have derived from a more distal source. In the section on the eastbank of the Tiber river, near Fratelle, a 'Contessa Bed' has been found in the Nero Member. Due to tectonic complications, the stratigraphic position of this bed could not be established. Thrusts bound the Nero Member to its upper and lower side. Its estimated minimum thickness is 1250 m.

Biostratigraphy

Biostratigraphic investigations have concentrated upon the dating of the 'Contessa Beds', found in all units of the Romagnan-Umbrian thrust zone.

From the detailed description of the 'Contessa Bed' (see e.g. Ricci Lucchi, 1975) it is clear that it is a very conspicuous quartz-arenitic turbidite with a characteristic lithologic composition and that it contains specific sedimentary structures. Among these are deep flutecasts which indicate a NW paleocurrent direction and a SE origin of supply. On lithostratigraphic evidence Ricci Lucchi correlated all occurrences of 'the Contessa Bed' within the region and claimed them to be the result of one, basin-wide turbidity current.

To check this, samples were taken from the marls directly underlying and covering the 'Contessa Beds' from all tectonic units:

1. Nero unit: 'Contessa Bed' from the section along the eastbank of the Tiber river, near Fratelle (Table 1, samples 1 and 2).
2. Castellaccio unit: 'Contessa Bed' from the transition zone between the Scalacci Member and the San Paolo Marls, directly S of San Paolo (Table 1, samples 3, 4 and 5).
   : 'Contessa Bed' cropping out directly NE of the Ligurian complex (Fig. 2), near Casa Val di Stenti (Table 1, samples 6 and 7).
3. Berleta-Civorio unit: 'Contessa Bed' cropping out in the fundaments of the Castle of Civorio (Fig. 2) (Table 1, sample 8).
4. Rullato unit: 'Contessa Bed' cropping out directly S of the village of Rullato (Fig. 2) (Table 1, sample 9).

The results of the investigations of the planktonic foraminifera and calcareous nannoplankton, which were kindly supplied by W.J. Zachariasse and B.W.M. Driever, are given in Table 1.

From the samples, number 7 did not contain any foraminifera, whereas numbers 6 and 8 were devoid of calcareous nannoplankton. Samples 1 to 9 were all taken from marls directly underlying or covering 'Contessa Beds'. Sample 10 originates from the base of the San Paolo Marls, in their type locality, whereas sample 11 was taken from the top of these marls. Table 1 shows that samples 3–9 all contain foraminifera from the same interval of the *Globorotalia peripheroronda* zone. The foraminifera of samples 1 and 2 are somewhat less specific

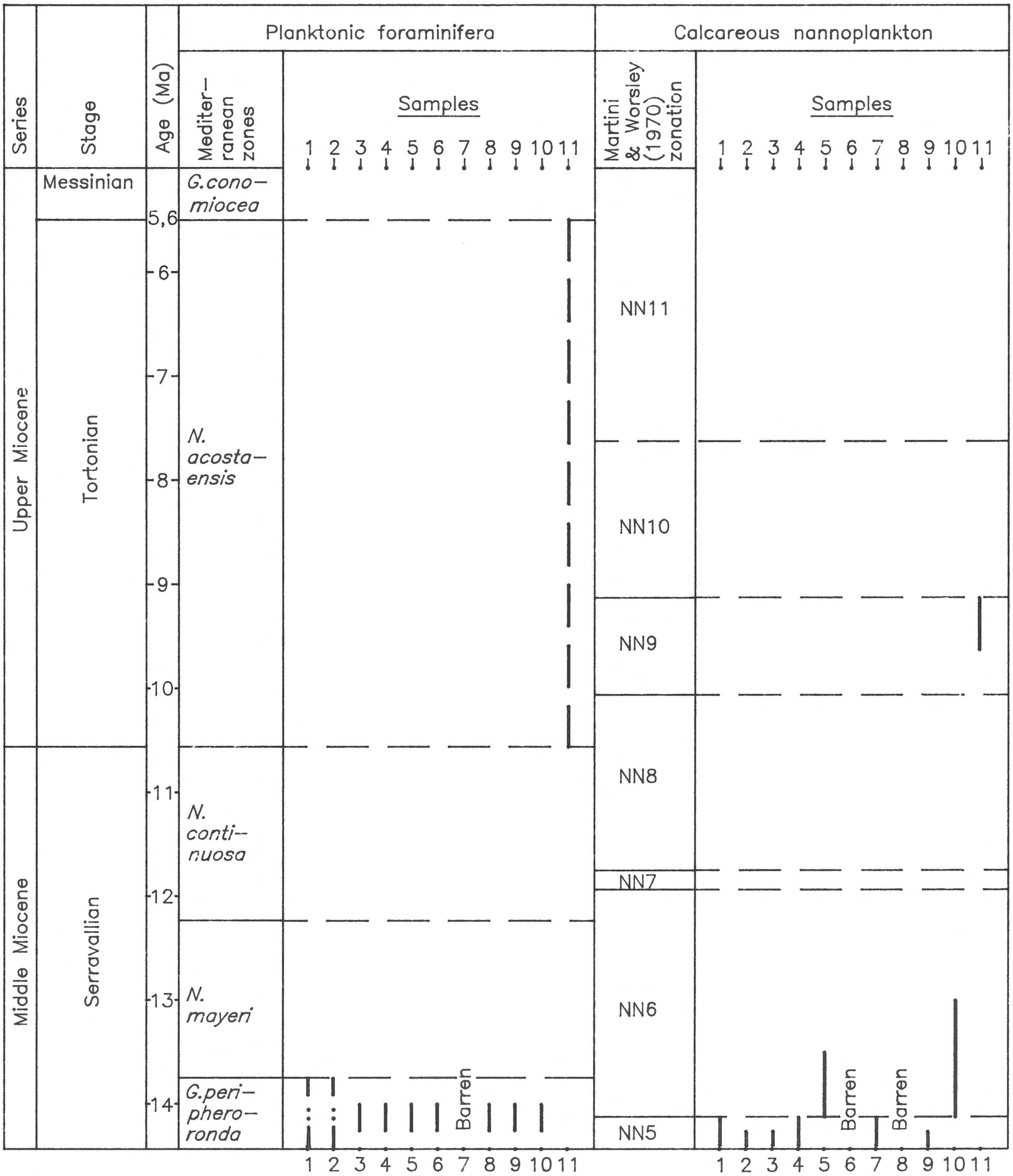


Table 1. Results of the biostratigraphic investigations of the study area. Samples 1–9 were taken from marls directly underlying or covering the 'Contessa Beds' of different tectonic units within the Romagnan-Umbrian thrust zone. Sample 10 is from the base-, and sample 11 is from the top of the San Paolo Marls in their type-locality. Determinations and interpretations by W.J. Zachariasse and B.W.M. Driever. For a discussion of the results see the text.

but they certainly also indicate the *Globorotalia peripheroronda* zone.

Moreover, the nannoplankton of samples 1–9 indicate zone NN5, except for sample 5, which would indicate the lower parts of zone NN6. As, however, the basal part of zone NN6 is a time equivalent of the *Globorotalia peripheroronda* zone, one may conclude from Table 1 that both the foraminifera and nannoplankton of samples 1–9 are 14–14,5 Ma old. These results, in our opinion justify the conclusion that the 'Contessa Beds' most probably are the result of one single turbidity current, that was triggered 14–14,5 Ma ago, during the Early Serravallian.

From Table 1 important conclusions may also be drawn, concerning the ages of the base and top of the San Paolo Marls. The foraminifera and nannoplankton of sample 10 indicate that the base is approximately 13,5–14 Ma old (= Early Serravallian). The nannoplankton of sample 11 dates the top of the San Paolo Marls, directly underlying the Ligurian thrust, at 9–10 Ma (= Early-Middle Tortonian). The plankton/benthos ratio of the foraminifera fauna of sample 11, moreover, is very small. This indicates that the upper part of the San Paolo Marls was deposited in a shallow marine (less than 200 m) environment. Thus, in its type area the 150–200 m thick San Paolo Marls appear to have been deposited during a period of approximately 4–4,5 Ma, while thick turbidite sequences seem to have accumulated simultaneously to the NE and SW (see Fig. 3). Together with the shallow marine depositional environment of its top, this indicates that the San Paolo Marls most probably were deposited on the culmination of an intrabasin high, where during a period of 4–4,5 Ma only a condensed section could accumulate. Sedimentation was abruptly terminated by the Ligurian overthrusting during the Early to Middle Tortonian.

Structural geology of the Romagnan-Umbrian complex.

The structural geologic interpretation, presented in this paper, is shown on the map of Fig. 2 and in the sections of Figs 4 and 5.

Folding is apparent in two, quite different ways:

a) Large-scale folding, characterized by an upright, symmetric, open fold geometry. The axial planes trend NW-SE. The anticline of Bagno di Romagna and the syncline of Santa Sofia (Fig. 2) are representatives of this folding. The direction of their axes is highly variable. Moreover, they seem to fold all thrust planes and the folds associated with them.

b) Small-, to large-scale folding, with different kinds of fold geometry, ranging from open, upright or slightly inclined symmetric folds, to tight and strongly inclined asymmetric folds. The axial planes trend NW-SE. All thcsc folds seem to be associated with thrusts. The symmetric folds predominantly occur in the hanging walls of the thrusts. In these cases they are interpreted as passive folds, generated in the hanging walls of thrusts with an irregular surface geometry (ramps and flats, see Figs 5a and b). The more or less asymmetric, largely synclinal folds, predominantly occur in the foot-walls of the thrusts and are always cut off by the thrusts. Within the hanging walls no asymmetric synclines have been found, asymmetric anticlines, however, do occur in the hanging walls (see e.g. within the Nero unit and Berleta-Civorio unit, Figs 2 and 5a, b). The foregoing, coupled to the fact that the thrusts always cut through their upright to overturned short limbs, indicates that the asymmetric folds must have been formed simultaneously with, or prior to the thrusts.

The balanced and restored sections of Fig. 5 suggest that there has been a direct relation between the generation of the large-scale asymmetric folds and thrusting (= fold-thrusting). The following sequence of events seems to be likely:

- After initial asymmetric folding,
- thrust planes developed at certain levels within the higher limbs of the folds, parallel to bedding,
- the thrusts cut through the short limbs at a high angle to the bedding without ramping of any importance,
- the thrusts proceeded in the lower limbs of the folds, parallel to the bedding again.

Closer examination of the geometry of the folds

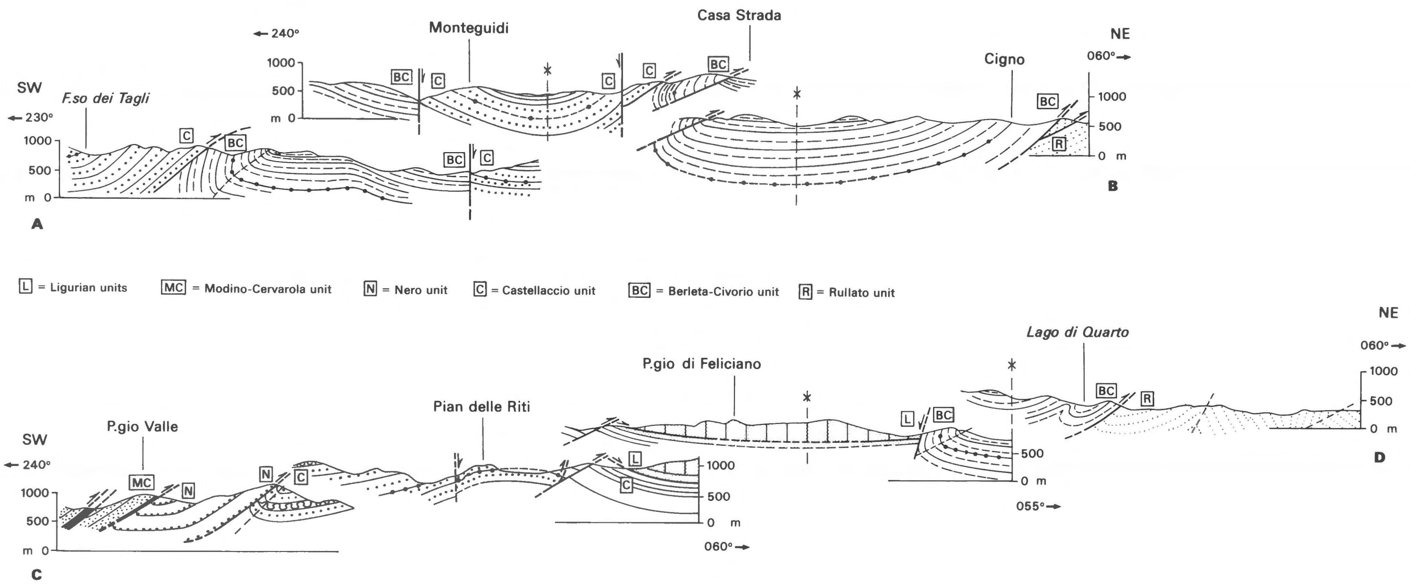


Fig. 4. Composite geologic sections (A–B and C–D) through the Romagnan-Umbrian thrust zone. For their locations see Fig. 2. Note that the scale is different from the map of Fig. 2. Legend as in Fig. 2, with hatching patterns following the general attitude of the bedding. (No vertical exaggeration).

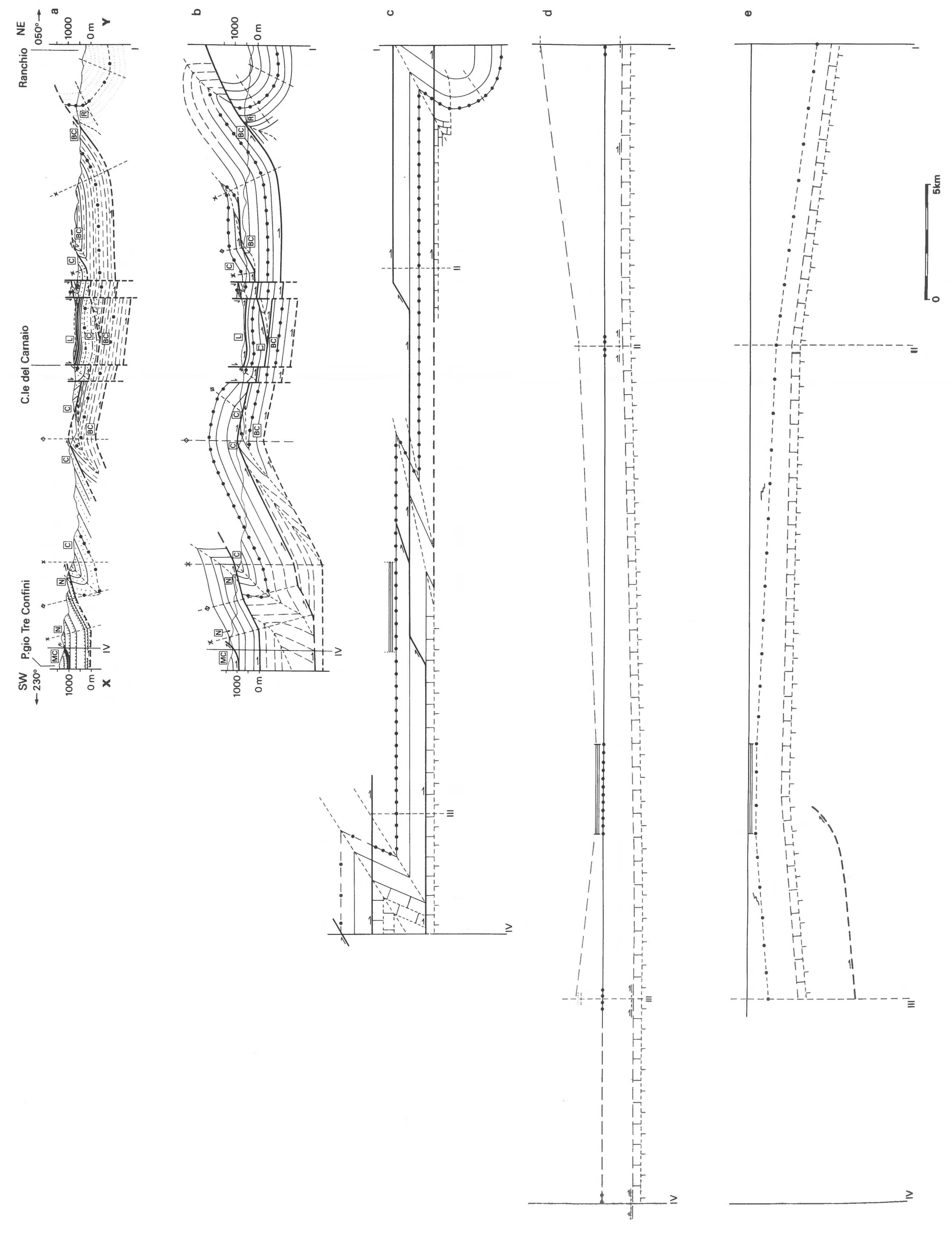
associated with the thrusting yields some interesting information on the tectonic regime in which the fold-thrusting has been developed. The sections of Figs 4 and 5 show, that folding was rather irregular. While the folds in the foot-wall, directly underneath the Nero thrust and the Castellaccio thrust are relatively regular in shape, the folds in the remaining Berleta-Civorio unit and in the Rullato unit certainly are not. The latter may have a box-like appearance with conjugate sets of axial planes. Moreover, real axial plane foliation with indications of pressure solution perpendicular to the foliation planes, have not been found within the area. Nor has an attenuation of any importance within the steep or overturned limbs of the folds been established. In our opinion these facts indicate the absence of principle stresses of any importance, which would have been active perpendicular to the axial planes of the folds during their generation. On the other hand, in the presence of detachment levels, gravitational sliding could have produced the conjugate folds and fold-thrusts. The thrusts may be defined in terms of thin-skinned tectonics, whereas both folding and thrusting could only develop in the presence of at least one important detachment level, originally present at different depths below the 'Contessa Bed' (see Figs 5a to d). The NW-SE trend of all thrust-folds and the NE-SW oriented thrust striation indicate a NE-SW oriented axis of maximal shortening. The asymmetry of the thrust-folds and drag structures moreover indicate a predominantly NE directed translation of the hanging walls of the thrusts.

From Figs 5c, d and e the position of the San Paolo Marls within the restored Romagnan-Umbrian turbidite basin segment may be examined. The thin San Paolo Marls appear to be coeval with much thicker turbidite sequences deposited in a basin plain environment to its NE (= Berleta and Civorio Member above the 'Contessa Bed') and to its SW (= Scalacci Member above the 'Contessa Bed'). Originally the San Paolo Marls may have had a wider distribution; in Figs 3, 5c, d and e only the proven occurrences have been reconstructed.

Structurally the San Paolo Marls appear to occur at the long SW-limb of an asymmetric anticline and above a ramp of the basal thrust of the Castellaccio unit (Figs 5c and d). The rock sequence above the 'Contessa Bed', NE from the San Paolo Marls, is incorporated in the asymmetric anticlinal folding, this proves that this fold developed after the deposition of the San Paolo Marls. Thus the development of this assymmetric fold can hardly be held responsible for the generation of the anticlinal culmination at which the condensed sedimentation of the San Paolo Marls took place. On the other hand, a ramp-structure and thrust movements underneath the San Paolo Marls certainly could. If, during or shortly after deposition of the 'Contessa' turbidite, thrusting were initiated with the appearance of blind thrusting, an anticlinal culmination must have developed in the hanging wall of this thrust (see Fig. 5e). This culmination would have persisted as an intrabasin high during the whole period of deposition of the San Paolo Marls (maximally 14–9 Ma). This would indicate that blind thrusting remained active during this period. An identical explanation has been given by De Jager (1979) for the development of the Castel Vecchio high in the Sillaro area. Later, from the Middle Tortonian onwards the Ligurian thrust over the San Paolo Marls, the asymmetric fold NE from the San Paolo high developed and it was subsequently cut by the basal thrust of the Castellaccio unit.

Apart from the main thrusts some minor thrusting and reverse faulting occurred within the thrust units especially in the Castellaccio unit and in the WSW part of the Berleta-Civorio unit (Fig. 2). These show the same northeasterly translation direction of their hanging walls.

High-angle faults also strongly control the outcrop pattern of the study area. A NW-SE trending dextral oblique-slip fault system controls the NE limitation of the Ligurian complex (Fig. 2) and almost totally cuts off the Castellaccio unit here. Figs 5a and b illustrate that the vertical component of translation along an individual dextral oblique-slip fault may be up to 700 m. From Fig. 2 the 'en-echelon' arrangement of the dextral oblique-slip faults is clearly apparent. The oblique character of these faults was established from the orientation of


Ranchio
NE
050°
a
1000
0 m
Y
C.le del Carnaio
P.gio Tre Confini
SW
230°
X
b
c
d
e
MC
N
C
L
BC
R
I
II
III
IV
0
5km

slip-striation and calcite fibres on fault scarps. Drag folding indicates that the NE blocks of the faults were relatively thrown up.

A NE-SW trending sinistral oblique-slip fault system was found between Bagno di Romagna and Verghereto (see Fig. 2). The vertical and horizontal components of the throw along these faults are much less, compared to the dextral oblique system mentioned above. Here also, the sinistral oblique character of the system has been established from slip-striation and calcite fibres on fault scarps and from the orientation of associated drag folds. Along the sinistral oblique-slip faults the NW blocks have been thrown up relatively.

If the dextral- and sinistral oblique-slip faults form part of a conjugate system, their orientation would indicate that the axis of maximum shortening was NNW-SSE during their development. Together with some normal faulting around San Piero in Bagno (Fig. 2) the oblique-slip faulting was the last important tectonic phase active within the area.

In summary, combination of the structural geologic and stratigraphic results reveals the following succession of sedimentary-tectonic events; (the sedimentary history of the Badia Prataglia Formation and Vicchio Marls is adopted from Ricci Lucchi & Ori, 1985).

- Late Oligocene – Aquitanian (± 25–22 Ma): Deposition of the Badia Prataglia Formation in the Modino-Cervarola turbidite basin.
- Burdigalian (possibly up to the Langhian) (± 22 – 19 (or 17) Ma): Closure of the Modino-Cervarola basin and condensed sedimentation of the Vicchio Marls.
- Langhian (= 19 – 15 Ma): Start of the subsidence of the Marnoso-arenacea (= Romagnan-Umbrian) turbidite basin.
- Early Serravallian (14,5 – 14 Ma): The 'Contessa Bed' was deposited in the Romagnan-Umbrian basin.
- Early Serravallian – Middle Tortonian (= 14 – 9 Ma): Development of the San Paolo intrabasin high, probably caused by an initial stage of blind thrusting that was active during the entire period. The development of blind thrusting may well be related to the initiation of thrusting of the Modino-Cervarola unit over the innermost Romagnan-Umbrian units. This period is marked by synsedimentary deformation (slumping) within the Romagnan-Umbrian turbidite basin (= D_o).
- Middle Tortonian (10 – 9 Ma): Ligurian units overthrust the San Paolo Marls, termination of deposition in the SW part of the Marnoso-arenacea turbidite basin (= D_{1a}).
- From the Middle Tortonian onwards (± 9 Ma–?): – First, the main folding and/or thrusting phase resulting in the Romagnan-Umbrian thrust zone. Because of its probable relation to the Ligurian thrusting, it is here defined as D_{1b}; – Open large-scale folding (e.g. formation of the Bagno di Romagna anticline) (= D_2).; – Generation of oblique-slip fault systems and normal faults (= D_3).

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Fig. 5a. The geologic section X–Y through the Romagnan-Umbrian thrust zone. For its location see Fig. 2. The tectonic units are indicated by the same symbols as in Fig. 4. Note that the scale is different from the map of Fig. 2 and the sections of Fig. 4. Legend as in Fig. 2 with hatching patterns following the general attitude of the bedding. (No vertical exaggeration).

Fig. 5b. The balanced section X–Y. The restoration was executed for the segment between I and IV only.

Fig. 5c. Partly restored section X–Y, after restoration of the effects of faulting and thrusting. The San Paolo Marls as well as the possible position of the calcareous basal part of the Romagnan-Umbrian sequence are schematically indicated.

Fig. 5d. Reconstruction of the minimum length of the 'Contessa Bed', within the segment between I and IV, just after deposition of the 'Contessa' turbidite (= 14,5 – 14 Ma). The San Paolo Marls and the possible position of the top of the calcareous part of the Romagnan-Umbrian sequence has been indicated schematically.

Fig. 5e. Reconstruction of the possible geometry of the Romagnan-Umbrian turbidite basin, just before the termination of the sedimentation by the Ligurian overthrust (10–9 Ma). The possible positions of the calcareous top of the Romagnan-Umbrian sequence, the 'Contessa Bed' and the blind thrust responsible for the San Paolo high, have been indicated.

The balancing and restoration of the Romagnan-Umbrian thrust zone

Now that we have evidence that the 'Contessa Beds', which are found in all thrust units of the Romagnan-Umbrian thrust zone, form part of one and the same marker bed, the Romagnan-Umbrian thrust zone can be reliably balanced and restored. Figs 5a to e show the results of the balancing and restoration of geological section X–Y (for its location see Fig. 2). The section (Fig. 5a) is oriented SW-NE, parallel to the reconstructed direction of translation along the thrust planes and perpendicular to the trend of the folds associated with the thrusts. Section X–Y shows that all thrusts and associated folds were refolded (see e.g. the anticlinal folding of the basal thrust of the Castellaccio unit SW of C.le del Carnaio). Moreover, the thrusts are cut by high-angle normal- as well as dextral oblique faults in the middle part of the section (see Fig. 2). As refolding is gentle and since stratigraphic markers were sufficiently clear within the blocks on both sides of the high-angle normal faults, these later deformation phenomena do not seriously hamper the balancing and restoration of this section. The same applies to the dextral oblique faults; their lateral translation is of minor importance (see Fig. 2). Thus through-section movements have been slight only.

The first step in the balancing procedure was to establish passive folds in the hanging walls of the thrusts. Secondly, the possible occurrence of hanging wall ramps was investigated. There are strong indications that a hanging wall ramp indeed is present in the Castellaccio unit SW of C. le del Carnaio (Figs 5a and b). In the third place the folds in the hanging- and foot-walls of the thrusts were examined and reconstructed. This certainly was the most difficult part of the procedure, as the fold geometry appeared to be highly irregular. Since the primary orientation of the large-scale asymmetric folds was unknown, we assumed that their long limbs originally had been horizontal (Fig. 5c). Although this may deviate slightly from the original situation, the relation between the bedding and the thrusts is not violated in this way and thus the errors should be small. The hanging wall ramp SW of C.le del Carnaio and the geometry of the tight folds directly underneath (see Fig. 5b), were both crucial for the establishment of the amount of translation along the basal thrust of the Castellaccio unit. According to our reconstruction this translation must have been at least 9,5 km, measured along the thrust plane.

The amount of translation along the basal thrust of the Nero unit can only be expressed by a minimum value. This is due to the absence of the 'Contessa' marker bed within the Nero unit here. According to our reconstruction the minumum amount is about 2 km, measured along the thrust plane.

The amount of translation along the basal thrust of the Berleta-Civorio unit cannot be established directly within section X–Y (see Fig. 5a). An overturned anticline in the frontal part of the Berleta-Civorio unit immediately NW of section X–Y (see Fig. 2) could be transposed, enabling the reconstruction of this structure in our section (see Fig. 5b). From this reconstruction the minimum amount of translation along the basal thrust of the Berleta-Civorio unit appeared to be 1,2 km.

Restoration of the high-angle faults and thrusts resulted in the partly restored section X–Y (Fig. 5c). It shows the geometry of the folds that developed prior to- or simultaneously with thrusting, as well as the position of the levels of main detachment. The lowermost detachment level appears to be deeper below the 'Contessa Bed' SW of the indicated occurrence of the San Paolo Marls (or 'high'), than to the NE of it. As the basal hemipelagic pelites (Schlier and Bisciaro) of the Romagnan-Umbrian sequence are the most probable detachment level, Fig. 5c also indicates that the calcareous sequences below these pelites may well have been involved in the folding.

In Fig. 5d also the effect of folding has been restored, resulting in a reconstruction of the original length of the 'Contessa Bed', just after the 'Contessa' event (14,5–14 Ma). Also the position of the basal detachment level has been indicated in Fig. 5d, giving some idea of the basin geometry during the period from the deposition of the basal pelites (Schlier, Bisciaro) until the 'Contessa' event. To reconstruct the possible basin geometry after the 'Contessa' event, the upper surface of the San Paolo Marls was connected with the top of the youngest sediments of sections I, II and III by means of correlation lines. Fig. 5e has been constructed by leveling these correlation lines to a horizontal position. In this way, the geometry of the San Paolo high could be approximated. Also the location of the blind thrust, responsible for the generation of this high, is schematically indicated with a heavy dashed line in Fig. 5e. It must have originated from a deep detachment level, possibly the Triassic evaporites. Finally, Fig. 5e gives an idea of the basin-fill geometry of the Romagnan-Umbrian basin just before sedimentation was terminated by the Ligurian overthrust (10 – 9 Ma). It indicates that since generation of the San Paolo high (beginning about 14 – 13,5 Ma), the centre of maximum sedement accumulation had shifted to the NE.

A comparison of the reconstructed length of the 'Contessa Bed' (Fig. 5d, between I and IV) with the length of the original section (Fig. 5a, between I and IV) reveals that the minimum amount of its total shortening is about 24,2 km. The minumum amount of its shortening due to folding (= reconstructed length Fig. 5d minus the length of section Fig. 5c) is about 11,8 km. The minimum amount of its shortening due to thrusting (= length of section Fig. 5c minus the original length of the balanced section Fig. 5a or b) is about 12,4 km.

Or, expressed in percentages of the reconstructed length of the 'Contessa Bed', its minimal total shortening was 48%. Folding accounted for about 49% and thrusting for about 51% of the total amount of shortening.

Conclusions

The initial subsidence of the Romagnan-Umbrian turbidite basin started during the Langhian (= 19 – 15 Ma). Biostratigraphic evidence indicates that one time-equivalent marker bed (the 'Contessa Bed') occurs in all tectonic units of the Romagnan-Umbrian thrust zone. This marker bed appears to be one single turbite, which accumulated in the Romagnan-Umbrian basin during the Early Serravallian (= 14,5 – 14 Ma).

The balancing and restoration of the Romagnan-Umbrian thrust zone indicates that during the 'Contessa' event, the Romagnan-Umbrian turbidite basin had a minimum width of 50 km, measured in NE-SW direction.

From the Early Serravallian to the middle Tortonian (= 14 – 9 Ma) an intrabasin high (= the San Paolo high) developed during an initial stage of blind thrusting. The blind thrust, assumed to be responsible for the development of the San Paolo high, originated at a detachment level below the Tertiary part of the Romagnan-Umbrian sequence, most probably within the Triassic evaporites. The NW-SE elongated San Paolo high divided the Romagnan-Umbrian basin into a SW and a NE subbasin. Since the generation of the San Paolo high the centre of maximum sediment accumulation shifted to the NE within the Romagnan-Umbrian basin. On the SW slope of the San Paolo high the Verghereto Marls have been deposited.

Sedimentation was terminated in the SW part of the Romagnan-Umbrian basin by the Ligurian overthrusting during the Middle Tortonian (= 10 – 9 Ma).

From the Middle Tortonian onwards (= about 9 Ma to ?) the main phase of folding and/or thrusting resulted in the development of the Romagnan-Umbrian thrust zone. During this phase the 'Contessa Bed' was shortened by a minimum of 48%. Folding accounted for about 49% and thrusting for about 51% of the total shortening. Later, large-scale folding, oblique-slip faulting and normal faulting overprinted the Romagnan-Umbrian thrust zone.

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