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Palaeotectonic significance of gravity displacement structures in the Miocene turbidite series of the M. Pollo Syncline (Umbro-Marchean Apennines, Italy)

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Abstract

The Northern Apennines are characterized by more or less severely deformed clastic wedges which originated in elongate foredeeps. These foredeeps were generated successively at the expense of the Adriatic Foreland. A thick turbidite sequence accumulated in the Umbro-Romagnan Foredeep during the Middle to Late Miocene. The variability of this sequence indicates that sedimentation and deformation patterns migrated within individual foredeeps. Marked facies and thickness changes were caused by the successive subsidence of foredeep segments in response to ensialic shearing. Subsequent multi-level gravitational spreading resulted in the development of synformal sub-basins at a later stage of the turbidite cycle within the successive foredeep segments. The gravity displacement structures in the M. Pollo Syncline in the Umbro-Marchean Apennines support such a differentiation. Additional ensialic shearing caused the out-of-sequence evolution of some thin-skinned structures. Ultimately, these were preferentially affected by extension tectonics associated with Tyrrhenian crustal stretching.

Introduction

The Northern Apennines form an integral part of the peri-Mediterranean system of Alpine chains, which resulted from differential movements between Africa and Europe. The Neotethyan oceanic basement of the most internal Apenninic zone, the Ligurian Zone, was completely subducted during the Late Cretaceous to Eocene. Subduction was caused by the convergence of the Adriatic and Sardo-Corsican continental blocks of African and European origin, respectively. The sedimentary covers of these blocks were thrust onto the continental margins (Boccaletti et al., 1980). Continued crustal shortening subsequently resulted in the Apenninic orogeny and thrust the orogen in a northeasterly direction over the Adriatic Foreland.

Since the Late Triassic beginning of the Alpine cycle, a sequence of evaporites, platform carbonates and pelagic siliceous carbonates and marls had accumulated on the Hercynian basement of the Adriatic foreland. Clastic wedges accumulated in successively generated elongate foredeeps, from the Tuscan Zone to the more external Umbro-Marchean-Romagnan Zone. The Tuscan and Umbro-Marchean-Romagnan terrains became progressively incorporated in the evolving orogenic belt. Since they largely maintained their original relative positions, they are referred to as the autochthonous assemblage of the Northern Apennines (cf. Ricci Lucchi & Ori, 1985; Ricci Lucchi, 1986). This allochthonous assemblage comprises Ligurids and associated terrains that were emplaced on the autochthon by gravity translations.

The complex evolution of Apenninic foredeeps is exemplified in this paper by a reconstruction of the interaction between tectonics and sedimentation in a segment of the Umbro-Marchean-Romagnan Zone (Figs. 1 and 2).

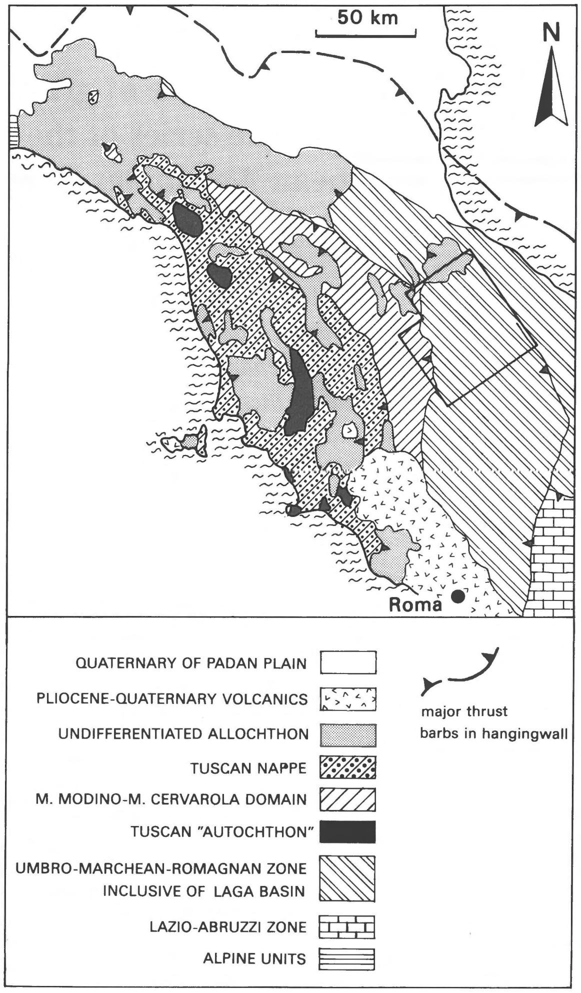

Fig. 1. The general structure of the Northern Apennines with an outline of Fig. 2. The buried thrust front of the Northern Apennines is marked with a dashed line.

Foredeeps and tectono-stratigraphic domains

Northern Apenninic foredeep sedimentation and deformation patterns migrated towards the stable Adriatic Foreland since the Oligocene (Merla, 1951; Bortolotti et al., 1970; Ricci Lucchi, 1975, 1981, 1986). A series of clastic wedges accumulated in consecutive longitudinal foredeeps. NW-SE trending tectono-stratigraphic domains (cf. Lavecchia et al., 1987), which are juxtaposed and partly superposed, resulted from the advancing, developping, orogen (Fig. 3). Their thrust displacement generally decreases towards the NE.

In the Tuscan Zone, the Tuscan Nappe and the more external M. Modino-M. Cervarola Domain contain the clastic wedges of the Inner and Outer Tuscan Foredeeps, respectively. The clastic wedges of the Umbro-Marchean-Romagnan Zone do not correlate as well with individual tectono-stratigraphic domains. The internal portion of the clastic wedge of the Umbro-Romagnan Foredeep comprises the Umbro-Romagnan parautochthon, while its external portion belongs to the Umbro-Marchean-Romagnan autochthon. This last domain is adjacent to the stable Adriatic Foreland to the NE. It also comprises deposits that originated in the marginal Laga Foredeep and the complex Padan-Marchean-Adriatic Foredeep. Sedimentation and deformation still continue in the Marchean offshore (Ori et al., 1986).

Foredeep sedimentation and tectonics

Turbiditic sedimentation, with a generally longitudinal dispersal, prevailed in the Northern Apenninic foredeeps with exception of the Padan-Marchean-Adriatic Foredeep. The turbidite sequences are typically tripartite (Fig. 4), comprising a prototurbiditic marly basal part, a conspicuous arenaceous-marly orthoturbiditic interval and a largely

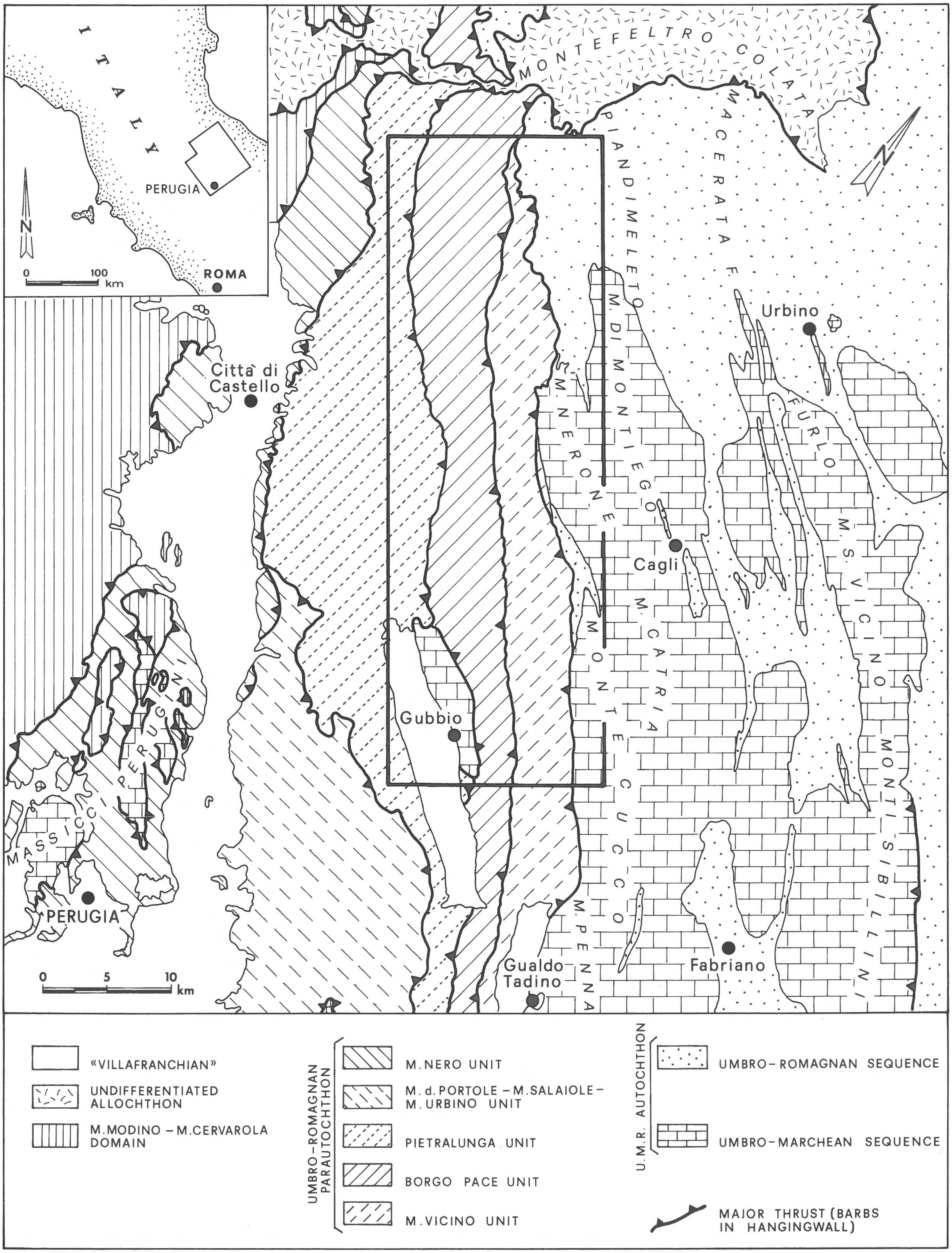

Fig. 2. Geologic scheme of the northern part of the Umbro-Marchean Apennines, showing principal positive structures (partly after Damiani et al., 1983; De Feyter et al., 1986; Menichetti & Pialli, 1986). Area of Fig. 6 is indicated.

<table>
<tr><td>STRUCTURAL CLASSIFICATION</td><td colspan="10"></td><td>PALAEOGEO-GRAPHIC CLASSIFICATION</td></tr>
<tr><td>COMPLEX</td><td colspan="2">TUSCAN ★</td><td colspan="8">UMBRO-MARCHEAN-ROMAGNAN ★</td><td>ZONE</td></tr>
<tr><td rowspan="2">DOMAIN</td><td>TUSCAN NAPPE</td><td>M.MODINO M.CERVA-ROLA</td><td colspan="5">UMBRO-ROMAGNAN PARAUTOCHTHON</td><td colspan="3">UMBRO-MARCHEAN-ROMAGNAN AUTOCHTHON</td><td rowspan="2">FOREDEEP</td></tr>
<tr><td>INNER TUSCAN</td><td>OUTER TUSCAN</td><td colspan="7">UMBRO-ROMAGNAN</td><td>LAGA</td></tr>
<tr><td rowspan="2">SUB-DOMAIN</td><td colspan="2" rowspan="3"></td><td colspan="2">INTERNAL UMBRO-ROMAGNAN PARAUTOCHTHON</td><td colspan="3">EXTERNAL UMBRO-ROMAGNAN PARAUTOCHTHON</td><td colspan="2" rowspan="2">OUTER UMBRO-ROMAGNAN</td><td rowspan="3"></td><td rowspan="2">FOREDEEP SEGMENT</td></tr>
<tr><td colspan="2">INNER UMBRO-ROMAGNAN</td><td colspan="3">CENTRAL UMBRO-ROMAGNAN</td></tr>
<tr><td>UNIT</td><td>M.NERO ★</td><td>POGGIO CASTEL-LACCIO ★</td><td>PIETRA-LUNGA ★</td><td>BORGO PACE ★</td><td>M.VICINO ★</td><td>INTERNAL</td><td>EXTERNAL</td><td>SUB-BASIN</td></tr>
<tr><td></td><td>I</td><td>II</td><td>III</td><td>IV</td><td>V</td><td colspan="2">VI</td><td>VII</td><td>VIII</td><td>IX</td><td></td></tr>
<tr><td rowspan="2">TEN HAAF & VAN WAMEL (1979)</td><td rowspan="2"></td><td rowspan="2">FALTERONA NAPPE</td><td colspan="2">ULTRA-ROMAGNAN</td><td colspan="5">ROMAGNAN</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>NERO UNIT</td><td>CASTEL-LACCIO UNIT</td><td colspan="3">PARAUTOCHTHON</td><td colspan="2">AUTOCHTHON</td></tr>
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Fig. 3. Tectono-stratigraphic elements of the autochthonous assemblage of the Northern Apennines, with emphasis on the Umbro-Marchean Apennines. The Poggio Castellaccio Unit represents a counterpart of the M. delle Portole/M. Salaiole-M. Urbino Unit. For comparison the classification applied by Ten Haaf & Van Wamel (1979) is shown. Elements with a combined structural and palaeogeographic significance are marked with an asterisk. Roman numbers refer to sections of Fig. 4.

marly cataturbiditic top part (Bortolotti et al., 1970; Sagri, 1973; Burger et al., 1978).

The clastic wedges frequently display gravity displacement structures and lateral facies and thickness variations. This points to the synsedimentary development of longitudinal ridges, not only between, but also within individual foredeeps (De Jager, 1979; Ricci Lucchi & Ori, 1985; Ten Haaf, 1985; Ori et al., 1986). This morphology was caused by detachment tectonics that affected the substrata of the pertinent foredeeps. Usually, a sole fault developed in Upper Triassic evaporites above the Hercynian basement. Additional significant detachments took place in the prototurbiditic marls at the base of some clastic wedges, accentuating the bipartite character of the sedimentary cover.

General stratigraphy and structure of the Umbro-Marchean Apennines

The southern sector of the Umbro-Marchean-Romagnan Zone is formed by the Umbro-Marchean Apennines. They are separated from the Romagnan Apennines to the northwest by the Montefeltro Colata, a transversal gravity flow of allochthonous terrains (Figs 1 and 2). The pre-turbiditic Umbro-Marchean Sequence and the overlying largely turbiditic Umbro-Romagnan Sequence form the sedimentary cover of the external portion of the Northern Apennines (Fig. 5).

The base of the Umbro-Marchean Sequence is formed by the Upper Triassic Burano Anhydrites Formation. This formation is overlain by massive platform carbonates of the Liassic Calcare Massiccio Formation and Liassic to Middle Eocene pelagic siliceous carbonates and marls (Corniola, Rosso Ammonitico, Calcari Diasprini, Maiolica, Marne a Fucoidi and calcareous Scaglia Formations). The Middle Eocene to Lower Miocene upper part of the Umbro-Marchean Sequence consists of the marly Scaglia and the calcareous-marly Bisciaro Formation.

The overlying Umbro-Romagnan turbidite sequence comprises prototurbiditic marls of the Middle Miocene Schlier Formation, the thick orthoturbiditic Marnoso-arenacea (i.e. marly-arenaceous)

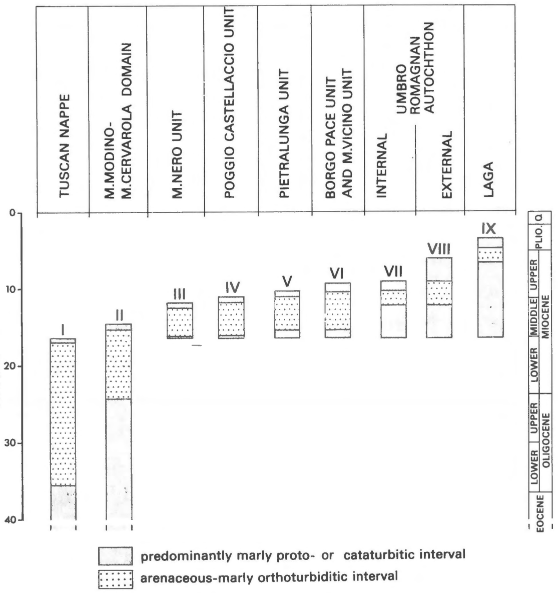


Fig. 4. Temporal distribution of tripartite turbidite sequences in the autochthonous assemblage of the Northern Apennines. The migration of foredeep sedimentation patterns towards the stable Adriatic Foreland to the right is evident. Ages are partly from Bortolotti et al. (1970), Damiani et al. (1983) and Günther & Reutter (1985).

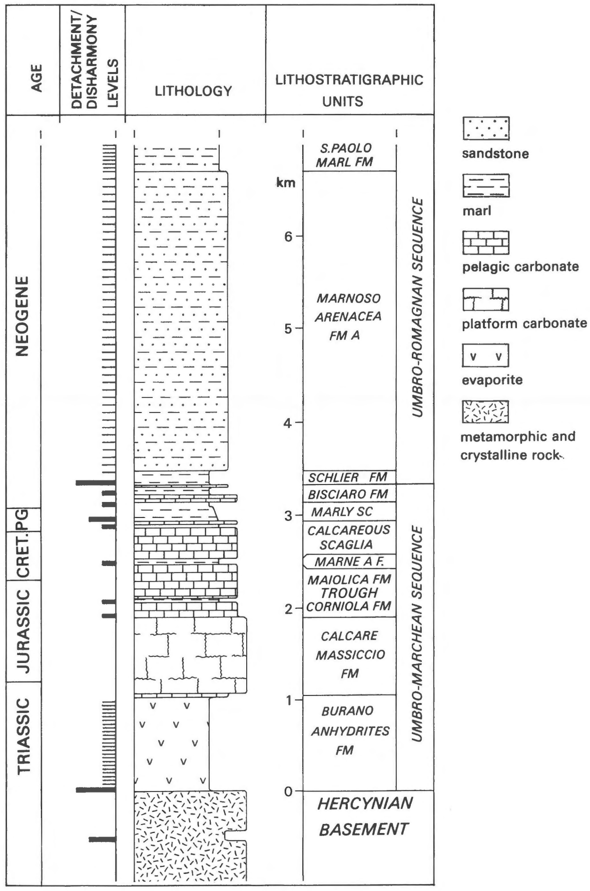


Fig. 5. Lithostratigraphy of the southwestern part of the Umbro-Marchean Apennines. The relative importance of detachment/disharmony level increases with length of bar. Note how their distribution reflects the competence variability.

Formation of Middle to Late Miocene age, and Upper Miocene cataturbiditic marls with some arenaceous intervals. The Marnoso-arenacea Formation is subdivided in an internal ('A') and an external ('B') variety. Messinian evaporites and younger molasse deposits form the top of the Umbro-Romagnan Sequence to the NE.

The Umbro-Marchean Apennines are a thin-skinned fold-and-thrust belt with longitudinal chains of more or less severly faulted brachyanticlines and complex highs, separated by synclinal zones with isolated positive structures (Fig. 2). A sole fault, generally situated in the incompetent Burano Anhydrites Formation, separates the deformed sedimentary cover from the largely subhorizontal Hercynian basement, as demonstrated by gravimetric and refraction seismic surveys (Pinna & Giannessi, 1981; Lavecchia et al., 1984). The anticlinal chains originated simultaneously through buckling, whereby the competent Calcare Massiccio Formation acted as the dominant member of the detached cover. Failure of this formation in the cores of the incipient anticlines induced stepped thrusting, which affected the chains successively towards the NE, causing accentuated and asymmmetrical fold shapes (Selli, 1952; Lavecchia, 1981; De Feyter et al., 1986; Lavecchia et al., 1987). Upper flats commonly developed in the marly intervals near the contact between the Umbro-Marchean and Umbro-Romagnan Sequences. Splay thrusting and tight folding of the overlying terrains accommodated the superficial shortening in the crestal zones of more external anticlines (De Feyter & Menichetti, 1986; Pieri & Mattavelli, 1986). Despite its displaced character, this deformed cover is ascribed to the Umbro-Marchean-Romagnan autochthon, since only discontinuous thrusts separate it from the stable Adriatic Foreland (Decandia & Giannini, 1977).

The autochthon solely comprises the Umbro-Marchean Sequence in the internal part of the Umbro-Marchean Apennines. It is exposed in several relatively isolated anticlines. The overlying Umbro-Romagnan terrains form an independently deformed thrust sheet (Jacobacci et al., 1970; De Feyter et al., 1986). This superficial parautochthon was translated several kilometres towards the stable Adriatic Foreland along a detachment surface at the base of the Umbro-Romagnan turbidite sequence. The parautochthon overrides the more external autochthonous Umbro-Romagnan terrains at a major thrust front, which can be traced through the Romagnan Apennines to the NW (Ten Haaf & Van Wamel, 1979; De Feyter et al., 1986).

Major normal faults dissect the compressive features in the internal portion of the Umbro-Marchean Apennines. They originated during the Late Pliocene to Pleistocene in response to crustal stretching associated with the opening of the Tyrrhenian Sea (Lavecchia et al., 1984, 1987).

Tectono-stratigraphic units of the parautochthon

Typical of the Umbro-Romagnan parautochthon are NE-facing asymmetric synclines separated by SW-dipping reverse listric faults of considerable longitudinal continuity, the so-called '*struttura romagnola*' (Signorini, 1941, 1956; Selli, 1952). These dislocations fade into asymmetric anticlines especially in the northwestern part of the Romagnan Apennines (De Jager, 1979; Ten Haaf & Van Wamel, 1979; Ten Haaf, 1985). The major structures are of synsedimentary origin as evidenced by transversal facies and thickness variations and gravity displacement structures (Ricci Lucchi & Ori, 1985; Ricci Lucchi, 1986). The synclinal blocks are therefore classified as tectono-stratigraphic units. The different ages of turbidite stages in the consecutive units (Fig. 4) demonstrate that sedimentation patterns and deformations in the corresponding sub-basins of the Umbro-Romagnan Foredeep migrated discontinuously towards the stable Adriatic Foreland in accordance with the general Apenninic picture (Micarelli, 1969; Ricci Lucchi, 1975, 1981, 1986; Damiani et al., 1983; Cantalamessa et al., 1986; Menichetti & Pialli, 1986; Lavecchia et al., 1987). Units belonging to one sub-domain merely differ in the upper parts of their sedimentary successions, which points to their relatively late individualization. Larger stratigraphic divergences between units belonging to different sub-domains indicate an earlier separation. The degree of stratigraphic discrepancy is thus of palaeotectonic significance.

The M. Nero Unit and the composite M. delle Portole/M. Salaiole-M. Urbino Unit are the most internal units of the parautochthon in the Umbro-Marchean Apennines (Fig. 2). The M. delle Portole/M. Salaiole-M. Urbino Unit is possibly an equivalent of the Poggio Castellaccio Unit defined in the Romagnan Apennines by Ten Haaf & Van Wamel (1979). In the more external parautochthonous sub-domain, comprising the Pietralunga, Borgo Pace and M. Vicino Units, the Marnoso-arenacea Formation A is bipartite. Its Upper Langhian to Middle Serravallian lower part consists predominantly of Austro-Alpine derived clastics that were supplied longitudinally from the NW. Volumetrically less important are calcareous turbidites, called '*colombine*', derived from the Lazio-Abruzzi carbonate platform to the south of the Umbro-Romagnan Foredeep, and 'Contessa' megaturbidites supplied by more internal mobile terrains of allochthonous affinity (Ricci Lucchi & Pialli, 1973; Centamore et al., 1977; Ardanese et al., 1983; Gandolfi et al., 1983). Sedimentation took place on a sub-horizontal basin plain as evidenced by the bimodal longitudinal dispersal pattern and the lateral continuity of individual turbidite layers (Ricci Lucchi, 1975, 1981, 1986). The contact between the Marnoso-arenacea and Schlier Formations in the frontal segment of the parautochthon is diachronous, indicating the external basin plain edge (Micarelli, 1969; Jacobacci et al., 1974; Centamore et al., 1977; Cantalamessa et al. 1986; De Feyter et al., 1986).

The Upper Serravallian to Lower Tortonian upper part of the Marnoso-arenacea Formation A is completely developed only in the external portion of the parautochthon. It is entirely composed of turbidites of NW origin, like the coeval Marnoso-arenacea Formation B of the adjacent autochthon.

The deposition of both varieties was progressively influenced by evolving longitudinal structures (Ricci Lucchi, 1975, 1981, 1986).

Thick cataturbiditic deposits accumulated subsequently in the synformal sub-basins of, in particular, the M. Vicino Unit and the adjacent autochthon. These deposits largely consist of material derived from more internal Apenninic source areas (Centamore et al., 1977).

Synsedimentary origin of the M. Pollo Syncline

The more or less asymmetric NE-vergent M. Pollo Syncline forms the Borgo Pace Unit (Figs. 6 and 7). This unit is juxtaposed and partly superposed on the M. Vicino Unit to the northeast along a reverse listric fault. A similar dislocation, which locally fades into an asymmetric anticline, separates the Borgo Pace Unit from the more internal Pietralunga Unit. Furthermore, it is flanked by the faulted brachyanticlinal structure of Gubbio, formed by Umbro-Marchean autochthonous terrains.

Up to 150 m of Lower to Upper Langhian prototurbiditic Schlier marls form the base of the Umbro-Romagnan turbidite sequence in the studied segment of the Borgo Pace Unit (Fig. 6). The overlying Upper Langhian to Middle Serravallian lower part of the Marnoso-arenacea Formation A has a thickness of more than 1500 m north of San Paolo di Fagnille. Its thickness gradually decreases towards the SE. The lower boundary gradually becomes younger in the same direction. The inferred basin plain depositional environment was largely unaffected by superficial tectonics, as indicated by the local obliquity of the palaeocurrent pattern to the principal compressive structures (Fig. 6). A similar slight obliquity is displayed by the NE-ward thinning and diachronism of the Marnoso-arenacea Formation A. This trend is restricted to the M. Vicino Unit near S. Paulo di Fagnille. Towards the southeast the same trend is displayed by the external limb of the M. Pollo Syncline as well.

The upper part of the Marnoso-arenacea Formation A near Borgo Pace consists of an Upper Serravallian mainly arenaceous interval. This interval occurs in the hinge zone of the M. Pollo Syncline, (Cantalamessa et al., 1986), affirming the Middle to Late Serravallian origin of the latter. There are no indications of massive turbiditic sedimentation after the basin plain stage further to the SE. Instead, the top part of the Marnoso-arenacea Formation A contains several SW-derived sedimentary gravity displacement structures. They are mainly of late middle to Late Serravallian age and are commonly situated near the hinge of the M. Pollo Syncline (Fig. 6). The major gravity displacement structures occur in depressions of the synclinal axis. This gives evidence for the primary origin of these axial depressions.

More or less lenticular poorly cemented arenaceous turbidites with abundant clayey clasts are associated with the major gravity displacement structures. These '*sale e pepe*' layers are local phenomena, resulting from the reworking of regular Marnoso-arenacea turbidite deposits southwest of the pertinent depressions.

S. Paolo di Fagnille slump sheet

The well-known S. Paolo di Fagnille slump sheet fills an axial depression of the M. Pollo Syncline at S. Paolo di Fagnille (Fig. 6) (Principi, 1931; Signorini, 1941; Jacobacci et al., 1970, 1974). This slump sheet has an areal extent of more than 5 km^2 and attains a thickness of almost 30 m near its northern and eastern margins. Its internal structure is bipartite there, with a strongly folded and faulted marly-arenaceous lower part and a predominantly marly upper part which displays more complex deformations (Fig. 8). Faults and attached folds at the base of the slump contain uprooted material from the otherwise undisturbed substratum. Dislocation surfaces with fibrous calcite and local cleavages in marly horizons are common in the lower part of the deformed level, similar to gravity displacement structures that are intercalated in the Umbro-Romagnan turbidite sequence elsewhere (De Jager, 1979; Ten Haaf & Van Wamel, 1979; Ten Haaf, 1985).

The northern and eastern marginal parts represent the toe of the slump sheet as indicated by the considerable thickness and contractional internal

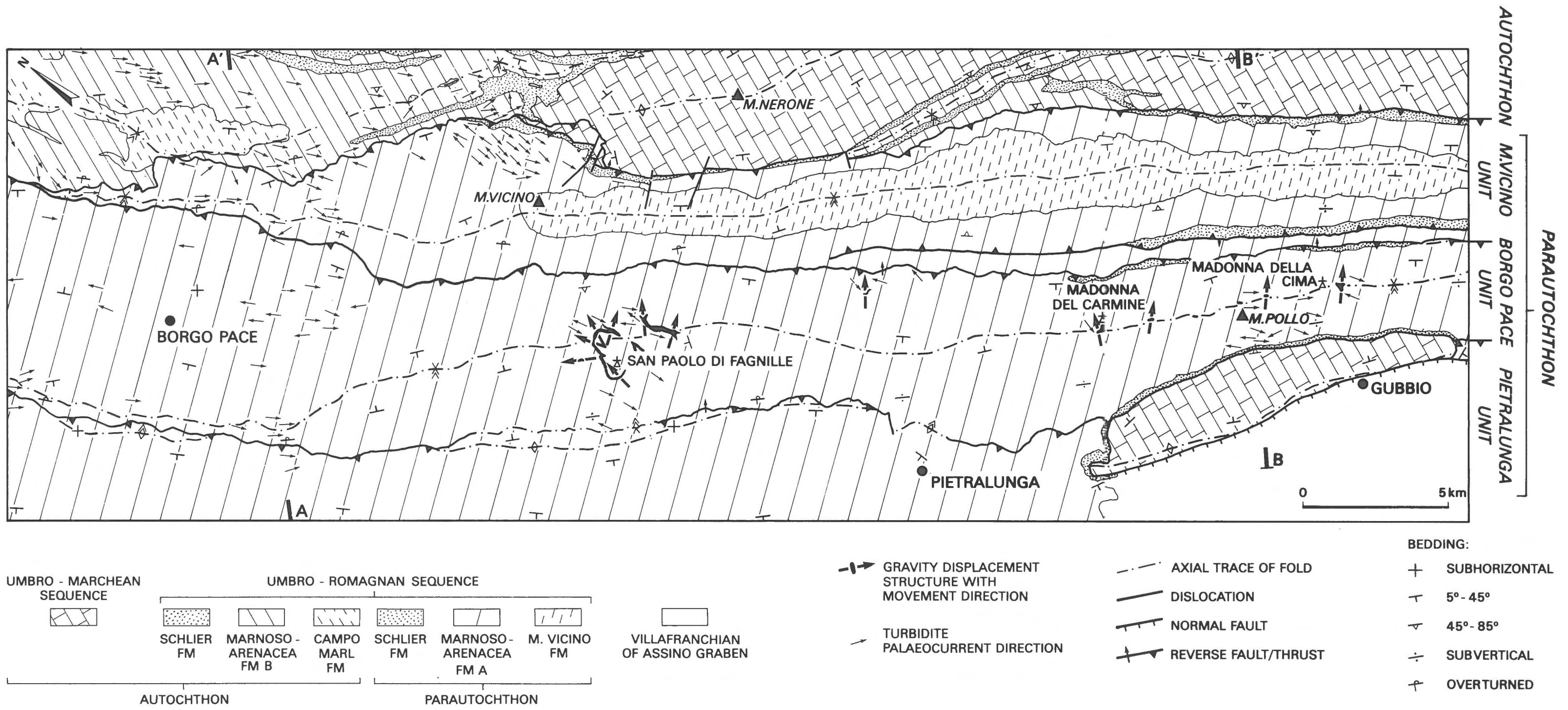


Fig. 6. Schematized geology of part of the Umbro-Marchean Apennines, as indicated in Fig. 2, showing the gravity displacement structures and palaeocurrent directions in the Borgo Pace unit. The traces of the cross sections of Fig. 7 are indicated.

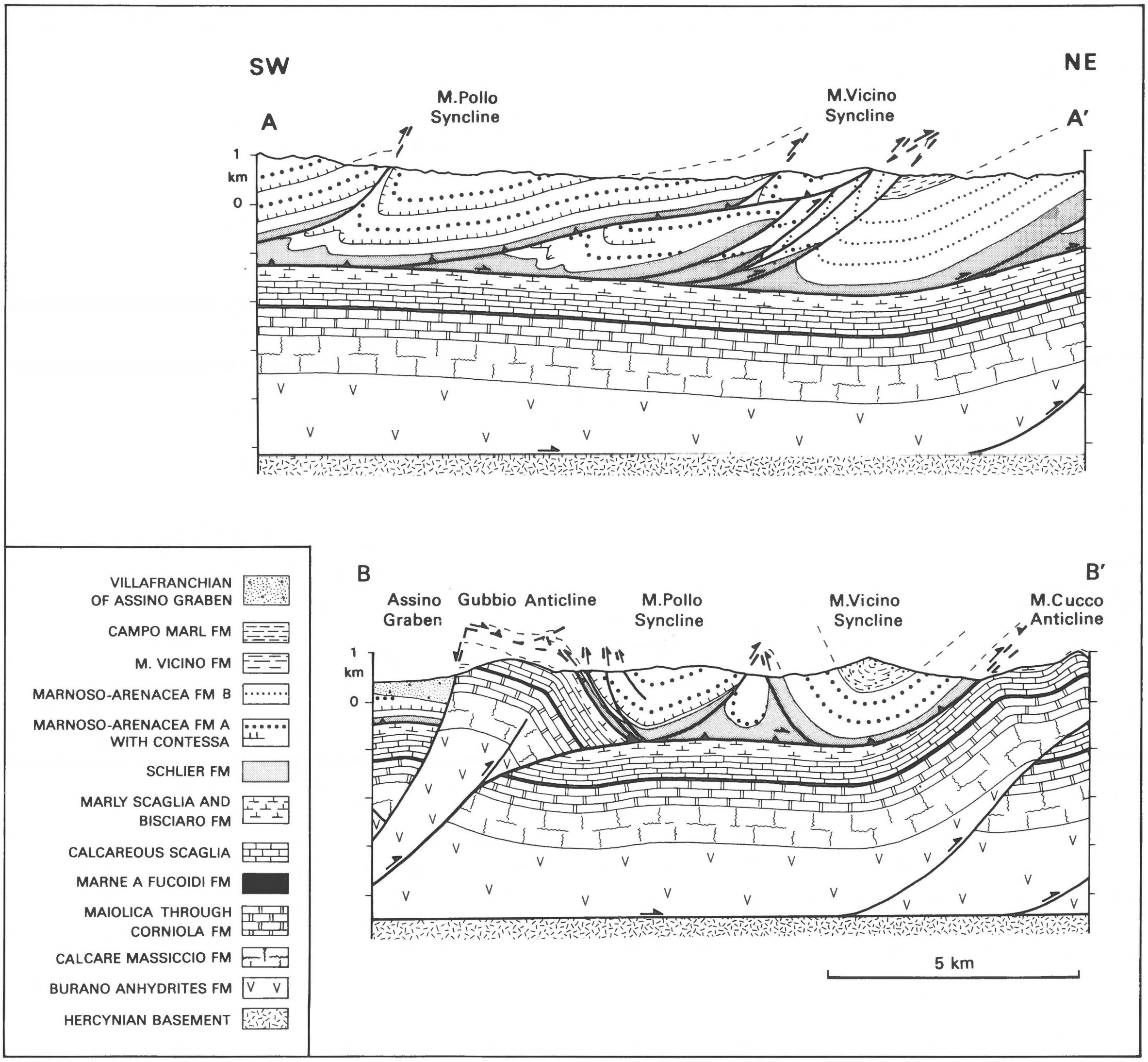


Fig. 7. Cross sections to Fig. 6 (B-B′ partly modified after De Feyter & Menichetti (1986) and Menichetti & Pialli (1986)).

deformations (cf. Lewis, 1971). The disturbed level at the western margin is largely marly and only a few metres thick, pointing to the proximity of the head of the slump. The orientations of synsedimentary deformation structures indicate NE-ward slumping down the internal limb of the M. Pollo Syncline, with a longitudinal deflection in its hinge zone.

Madonna del Carmine slump sheet

Near Madonna del Carmine (Fig. 6) the M. Pollo Syncline contains another, less extensive, marly-arenaceous slump sheet, which again is of SW origin. The folded and faulted toe of this structure lies on a very regular dislocation surface of fibrous calcite (Fig. 9). Its substratum is essentially undeformed with the exception of some low-angle fractures.

Fig. 8. The longitudinally deflected toe of the slump sheet of S. Paolo di Fagnille. Note the bipartite character of the slump sheet and the uprooted substratum. The same structures appear on either side of the semicircular outcrop, affirming the northward direction of slumping. A thick *colombina* turbidite stands out among the overlying turbidites. The maximum height of the outcrop is 60 m. The drawing is partly traced from photographs.

Fig. 9. Basal part of the toe of the slump sheet of Madonna del Carmine. A discrete surface with fibrous calcite (visible just above the thin whitish calcareous marl layer 1 m above the hammer) separates it from the markedly undeformed substratum. This is merely dissected by low-angle fractures, occasionally showing a minor reverse offset, that dip against the inferred NE-ward slumping direction.

Madonna della Cima detached flap

A number of complex deformation patterns can be recognized within the M. Pollo Syncline near Madonna della Cima (Figs. 6 and 10). A 30 m thick SW-derived gravity displacement structure with an areal extent of 0.01 km^2 is present at the top of the Marnoso-arenacea Formation A. Unlike the slump sheets described before, the constituting layers are mainly overturned. Severe disruption of layers is confined to the basal part of the structure and to several contractional listric faults branching off its basal dislocation surface. The displaced slab closely resembles the upper part of its substratum with respect to the lithostratigraphy. In front of it, the substrata are overlain by a shoved-up interval with thick *sale e pepe* turbidites and a minor slump sheet of SW origin, the result of sedimentation that was penecontemporaneous with the gravity displacement.

Signorini (1956) and Hsü (1967) interpreted overturned slabs of turbiditic terrains in the Northern Apennines as the lower limbs of possibly disrupted recumbent anticlines that face the direction of gravity displacement. The deformation style of such an overturned slab at Madonna della Cima points to a downslope movement of a detached overturned slab. More or less in accordance with the model proposed by Valduga (1950) and Maxwell (1959), this slab probably originated on the submarine slope bordering the M. Pollo Syncline to the southwest in the same way as a type of subaerial gravity collapse structures reported from the Zagros orogenic belt (Harrison & Falcon, 1934). Below an initial stratal disruption, possibly related to an earlier knee fold, superficial terrains could have bent over backwards under the influence of gravity

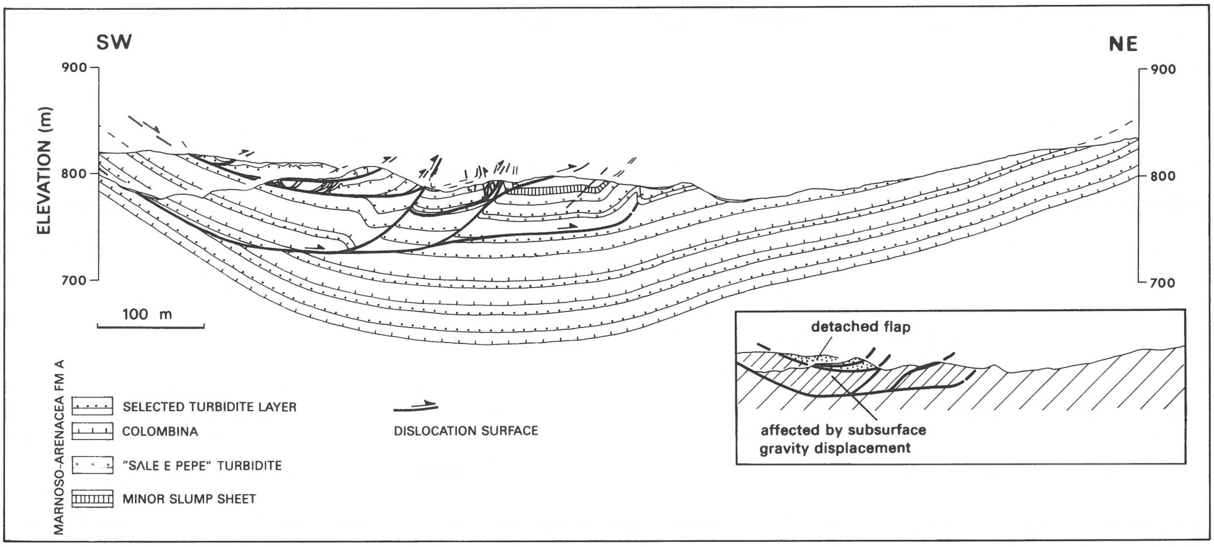


Fig. 10. Detailed section across the hinge zone of the M. Pollo Syncline at Madonna della Cima. Gravity displacement structures and cannibalistic *sale e pepe* turbidites, which are derived from the SW, lie on top of the basin plain succession of the Marnoso-arenacea Formation A. This reflects the synsedimentary generation of the syncline. Stratigraphic facing is indicated. The structural affiliations are shown in the inset.

to form a flap, i.e. the overturned upper limb of a NE-facing recumbent syncline. The flap grew at the expense of its substratum as the synclinal hinge migrated downslope, ultimately being detached and gliding towards its actual position.

The M. Pollo Syncline also displays deeper-seated contractional structures at Madonna della Cima. These evolved penecontemporaneously with the emplacement of the detached flap while the upper 60 m of the Marnoso-arenacea Formation A moved slightly downslope on the southwestern limb of the syncline. This is still considered a sedimentary gravity displacement process, although it approaches the dimensions of gravity tectonics (cf. Lewis, 1971).

Structural evolution of the Umbro-Romagnan Foredeep

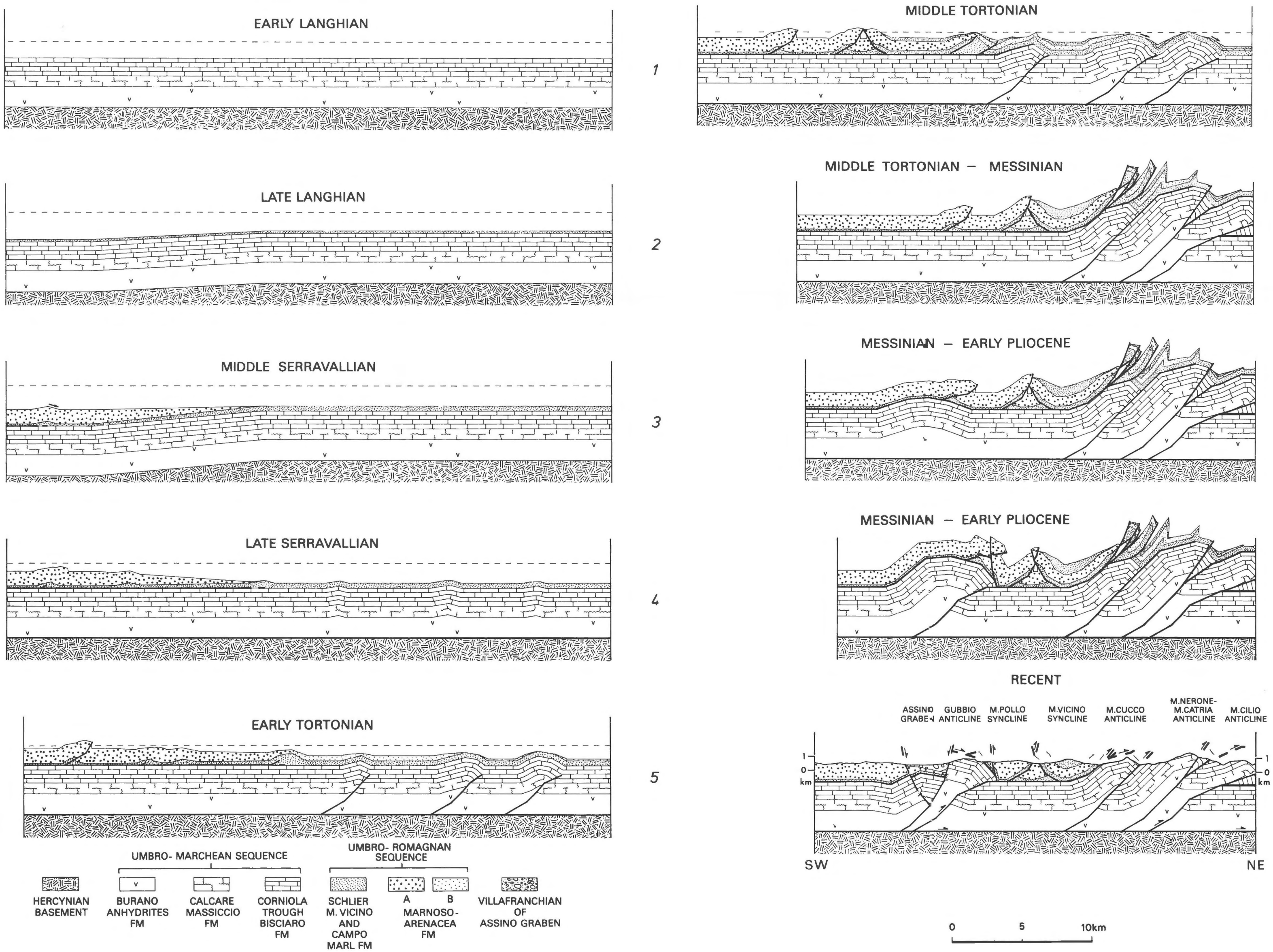
The spatial and temporal distribution of sedimentary phenomena reflects the tectonic processes that determined the evolution of the Umbro-Romagnan Foredeep. The markedly diverse ages of the turbiditic stages in the Ultra-Romagnan and Umbro-Romagnan sub-domains of the parautochthon and in the adjacent autochthon suggest that these originated as more or less individually subsiding foredeep segments. For instance, the 1500 m of Upper Langhian to Middle Serravallian Marnoso-arenacea A basin plain turbidites of the external Umbro-Romagnan parautochthon were deposited concurrently with about 200 m of prototurbiditic Schlier marls of the adjoining autochthon. This implies a considerable subsidence of the basin floor relative to the more external portions of the evolving foredeep. The latter subsequently subsided by a similar amount, as indicated by maximum thicknesses of about 2 km of the Upper Serravallian to Lower Tortonian Marnoso-arenacea B orthoturbidites in the autochthon. Superficial factors, such as deformations of the Umbro-Marchean substrata, were of little importance to these differential vertical movements. Instead, a flexural bending of the continental lithosphere beneath active foredeep segments must be invoked (e.g., Fig. 11, stages 1 through 4). Lavecchia et al. (1987) stressed the significance of superficial loading by evolving thrust sheets at the internal margin of the Umbro-Romagnan Foredeep. Despite the additional effect of rapid sedimentation in subsiding foredeep segments (Gretener, 1981), surface loads alone cannot account for the inferred flexural bending (Ricci Lucchi, 1986). In fact, the orthoturbiditic stage in the various segments of the Umbro-Romagnan Foredeep typically preceded major thrusting at their internal margin. Furthermore, the autochthonous assemblage of the Northern Apennines was mainly deformed by detachment tectonics, with extensive tectonic duplications restricted to the Tuscan Nappe. The overriding frontal segments of the thrust sheets usually consist of the thin marginal parts of the corresponding sedimentary units. Loading by allochthonous terrains could also not have been of great importance considering their patchy distribution. It is thus evident that subsurface loads played a vital role in the evolution of the Umbro-Romagnan Foredeep. The generation of successively subsiding foredeep segments and the associated migration of the onset of orthoturbiditic sedimentation were probably controlled by crustal imbrication along SW-dipping shear zones, moving discontinuously upon the Adriatic Foreland (Sagri, 1973; Boccaletti et al., 1980). A connection with similar ensialic shearing has been demonstrated for the Padan-Marchean-Adriatic Foredeep (Royden et al., 1987).

No deep-seated tectonics are required to account for the differentiations at a more advanced stage of the turbidite cycle within, as well as between, the principal foredeep segments. Ultimately, the various tectono-stratigraphic units resulted from this differentiation. The generation of the M. Pollo Syncline during the middle to Late Serravallian (Fig. 11, stages 3 and 4) was solely due to deformations above the evolving shallow detachment surface at the base of the future parautochthon. This is evidenced by the distribution of gravity displacement structures and arenaceous facies in the hinge zone of the M. Pollo Syncline irrespective of the autochthonous Gubbio Anticline to the southwest (Fig. 6). About coeval gravity displacement structures, predominantly derived from the SW, occur in a similar structural position in the other parautochthonous units of the Umbro-Marchean Apennines. The M. Vicino Unit contains some minor slumps northeast of San Paolo di Fagnille (De Feyter et al., 1986). Larger slumps and slides, accompanied by a few olisthostromes of Tuscan and allochthonous elements between Pietralunga and Gualdo Tadino, are present in the Pietralunga Unit (Jacobacci et al., 1970, 1974; De Feyter, 1982). The adjacent M. delle Portole/M. Salaiole-M. Urbino Unit displays numerous olisthostromes and olisthoplakhas of similar origin (Ricci Lucchi & Pialli, 1973; Damiani et al., 1983). The more internal M. Nero Unit comprises slumps north of Città di Castello. The most conspicuous counterparts of these Serravallian gravity displacement structures in the Romagnan Apennines are extensive slump sheets that are present in the Poggio Castellaccio Unit (Ricci Lucchi, 1975, 1981; De Jager, 1979; Ten Haaf & Van Wamel, 1979; Ten Haaf, 1985).

The M. delle Portole/M. Salaiole-M. Urbino Unit also contains olisthostromes of early Late Langhian age (Damiani et al., 1983; Menichetti & Pialli 1986). These olisthostromes belong to a generation of gravity displacement structures which only occur in the Internal Umbro-Romagnan subdomain of the parautochthon. Lower to Middle Tortonian gravity displacement structures on the other hand are more common in the M. Vicino Unit and the adjacent autochthon.

The distribution of the various generations of gravity displacement structures reflects the discontinuous advance of topographic differentiation towards the Adriatic Foreland. The topography was fashioned by deformation pulses affecting progressively larger portions of the Umbro-Romagnan Foredeep. Thus, the longitudinal sub-basins, wherein the tectono-stratigraphic units of the parautochthon accumulated, were outlined by asymmetric anticlinal highs generated at the tip of the intermittently propagating detachment surface which separated it from the autochthon. Subsequent reverse listric faulting accentuated and eventually disrupted these structures (Fig. 11, stages 4 through 6).

The sequential mild internal deformations of the relatively thin and incompetent parautochthonous thrust sheet indicate a NE-ward gravitational spreading (Elliot, 1976; Cooper, 1981). The validity of this mechanism is demonstrated by the penecontemporaneity of the incipient differentiation in the Inner Umbro-Romagnan foredeep segment at the beginning of the Late Langhian and the


EARLY LANGHIAN
1
LATE LANGHIAN
2
MIDDLE SERRAVALLIAN
3
LATE SERRAVALLIAN
4
EARLY TORTONIAN
5
MIDDLE TORTONIAN
6
MIDDLE TORTONIAN – MESSINIAN
7
MESSINIAN – EARLY PLIOCENE
8
MESSINIAN – EARLY PLIOCENE
9
RECENT
ASSINO GRABEN
GUBBIO ANTICLINE
M.POLLO SYNCLINE
M.VICINO SYNCLINE
M.CUCCO ANTICLINE
M.NERONE-M.CATRIA ANTICLINE
M.CILIO ANTICLINE
1
0
km
10
SW
NE
UMBRO- MARCHEAN SEQUENCE
UMBRO- ROMAGNAN SEQUENCE
HERCYNIAN BASEMENT
BURANO ANHYDRITES FM
CALCARE MASSICCIO FM
CORNIOLA TROUGH BISCIARO FM
SCHLIER M. VICINO AND CAMPO MARL FM
A B MARNOSO-ARENACEA FM
VILLAFRANCHIAN OF ASSINO GRABEN
0 5 10km

←
Fig. 11. Schematized tectono-stratigraphic evolution since the Early Miocene along a transect partly coincident with cross section B-B′ of Fig. 7. The Calcare Massiccio Formation serves as a reference level. Sea level is inferred where appropriate. Possible large-scale tiltings, cataturbiditic sedimentation within the M. Vicino Syncline, and syntectonic erosion are not shown. Gravity displacements are only indicated in the M. Pollo Syncline. Stage 1: Onset of prototurbiditic sedimentation. Stage 2: Onset of orthoturbiditic sedimentation on the subsiding Umbro-Romagnan basin plain, while prototurbiditic sedimentation persists more externally. Stages 3 and 4: Progressive differentiation of Umbro-Romagnan basin plain. The resultant gravity displacements in the incipient M. Pollo Syncline are indicated by an arrow. Relative subsidence determines the onset of orthoturbiditic sedimentation and additional thin-skinned deformations more externally. Stage 5. Continued multi-level detachment tectonics. Onset of cataturbiditic sedimentation in the M. Vicino Syncline and more externally. Stage 6: Continued multi-level detachment tectonics and cataturbiditic sedimentation. Stage 7: Principal translation of the Umbro-Romagnan parautochthon and thin-skinned deformation of the adjacent Umbro-Marchean-Romagnan autochthon. Stages 8 and 9: Superficial out-of sequence evolution of the Gubbio Anticline. Stage 10: Present-day situation, after the formation of the Assino Graben and erosion.

onset of orthoturbiditic sedimentation of the Marnoso-arenacea Formation A in the next external foredeep segment. Within the latter, the thickness of the Umbro-Romagnan deposits was not yet sufficient to allow the propagation of the superficial detachment tectonics (cf. Gretener, 1981). Longitudinal structures including the M. Pollo Syncline were moulded here by the deformation pulse of the middle to Late Serravallian. This deformation pulse also accentuated the Ultra-Romagnan sub-basins. Again, gravitational spreading was apparently caused by more external relative subsidence, where the orthoturbiditic Marnoso-arenacea Formation B started to accumulate (Fig. 11, stage 4). These Middle Miocene synsedimentary tectonics were sequential to similarly induced deformation pulses in the Outer Tuscan Foredeep, as indicated by the tectono-stratigraphic resemblance of the parautochthon and the M. Modino-M. Cervarola Domain (Günther & Reutter, 1985). Therefore, the Umbro-Romagnan parautochthon and the M. Modino-M. Cervarola Domain are probably underlain by a common shallow detachment surface (De Jager, 1979; Ten Haaf & Van Wamel, 1979).

The Early to Middle Tortonian gravity displacements mark the Late Miocene main translation of the parautochthon towards the Adriatic Foreland. They especially affected the synformal sub-basins next to the evolving thrust front as these were accentuated by hangingwall and footwall imbrication (De Feyter et al., 1986). Unlike the previous deformation pulses, the extensive Late Miocene gravitational spreading must be attributed to major uplift in more internal parts of the orogen (Boccaletti et al., 1980).

During the Early Miocene, mild buckling above the sole fault in the Burano Anhydrites Formation resulted in the emersion of incipient anticlinal chains in the autochthon, as indicated by thickness variations of the Bisciaro Formation (not shown in Figure 11). These anticlinal chains were notably amplified by further buckling and stepped thrusting from the Late Serravallian onward. Apparently, the levelling of the basement of the Umbro-Romagnan Foredeep at that time permitted the expansion of the thin-skinned tectonics (Fig. 11, stage 4). Their migration on a regional scale towards the Adriatic Foreland is compatible with gravitational spreading (Elliott, 1976; Cooper, 1981). The Umbro-Marchean Chain, composed of systematically arranged structures such as the M. Nerone-M. Catria and M. Cucco Anticlines (Fig. 2), evolved simultaneously with the shallower gravitational spreading of the more internal parautochthon. This is evidenced by severe deformations generated in anticlinal backlimbs which oppose the front of the latter (De Feyter et al., 1986).

The origin of the Gubbio Anticline

The faulted Gubbio Anticline is an autochthonous structure of Umbro-Marchean terrains, surrounded by the Umbro-Romagnan parautochthon (Figs 2, 6 and 7). Both its location and a relatively thin Bisciaro Formation suggest that it represents an anticlinal chain of Early Miocene origin. However, unlike the Umbro-Marchean Chain, it was not markedly amplified prior to the termination of the gravitational spreading of the parautochthon, as indicated by the linearity of more external longitudinal structures in the latter. The thick Umbro-Romagnan turbidite sequence of the parautochthon possibly inhibited thin-skinned deformation of the underlying Umbro-Marchean terrains (cf. Morley, 1987). The anticline probably developed by renewed buckling and stepped thrusting during the late Miocene to Early Pliocene (Fig. 11, stages 8 and 9). The detachment surface at the base of the parautochthon was reactivated as a forelimb back thrust, which accommodated most of the frontal hanging wall strain (De Feyter & Menichetti, 1986). Furthermore, out-of-the-syncline back thrusts and fore thrusts originated in the tightening M. Pollo Syncline, while more externally a triangle zone between the Borgo Pace and M. Vicino Units (Menichetti & Pialli, 1986) was slightly accentuated.

An orogenic process other than the regular gravitational spreading of the Umbro-Marchean-Romagnan autochthon must have generated the superficial out-of-sequence evolution of the Gubbio Anticline. The same applies to the more internal autochthonous structures of the Massicci Perugini (Fig. 2), since these did not interfere with the gravitational spreading of the parautochthon either. In fact, they are accompanied by thrusted basement slices, suggesting that they were amplified by ensialic shearing (Lavecchia et al., 1984, 1987). Accordingly, more external splaying could have amplified the Gubbio Anticline. However, the possibility that this anticline evolved directly above a separate basement shear zone cannot be excluded. After the relaxation of compressive stresses, the resulting structures were preferentially affected by normal faulting associated with the Tyrrhenian crustal extension. This is exemplified by the Late Pliocene to Pleistocene formation of the Assino Graben at the expense of the backlimb of the Gubbio Anticline (Fig. 11, stage 10). The regional importance of these inversion tectonics is demonstrated by the downfaulted backlimbs of the autochthonous anticlines of M. Subasio and Monti Martani further to the south, which possibly belong to the same arcuate chain as the Gubbio Anticline and likewise are situated amongst the parautochthon.

Conclusions

The tectono-stratigraphic evolution of complex foreland basin systems has been derived from the analysis of the spatial and temporal distribution of sedimentary features in the basin fill. In the paraotochthon of the Umbro-Marchean-Romagnan Zone, gravity displacement structures reflect the differentiation of turbiditic foredeep segments into synformal sub-basins due to superficial gravitational spreading, which in turn resulted from migratory ensialic shearing. Possibly, such sedimentary features have a similar palaeotectonic significance in the M. Modino-M. Cervarola Domain. The autochthon of the Umbro-Marchean-Romagnan Zone was deformed independently by deeper-seated gravitational spreading that locally was succeeded by ensialic shearing.

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