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# Map analysis techniques and fold kinematics in the Umbrian Apennines, Italy

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*Key words:* Map analysis techniques, hinge point tie lines, cutoff point tie lines, facing direction, breaching

ABSTRACT

The structure of southeastern Umbria (Central Apennines, Italy), as obtained with the use of map analysis techniques, integrated with observations on mesoscopic structures, is described. The strike of major fold and thrust structures is remarkably parellel, both at frontal and lateral or oblique ramps, suggesting a common origin for folding and thrusting. Folds at all scales strike parallel even when the minor structures are not consistent with the shearing sense expected for flexural-slip fold mechanisms: this indicates a multistage, progressive compressional deformation, resulting in a coaxial overprinting fold geometry. The complex structural evolution can be interpreted as due to simple breaching during the Neogene compression.

RIASSUNTO

Vengono definite la geometria e l'orientazione delle strutture maggiori affioranti nel settore meridionale dell'Appennino umbro-marchigiano-sabino (Italia centrale), tramite l'adozione di tecniche di analisi cartografica. Esiste uno stretto parallelismo fra le pieghe osservabili a qualunque scala; l'orientazione delle pieghe principali é sempre parallela alla direzione dei sovrascorriementi, sia in corrispondenza delle rampe frontali, che delle rampe oblique e laterali: questi rapporti suggeriscono un'origine di entrambe le classi di strutture per *thrust-related folding.* I sovrascorrimenti si propagano secondo una sequenza di tipo *piggy-back;* alla stessa sequenza va riferito lo sviluppo di mesostrutture il cui senso di taglio non é coerente con quello delle macropieghe che le contengono.

## A. Introduction

In the study of fold and thrust belts, the interpretation of map scale structures is greatly enhanced by observations at the outcrop scale: mesoscopic analysis is necessary to investigate in detail the overprinting relationships between different minor structures, and hence determine the deformation history and processes active during deformation of the sedimentary cover. Moreover, measurements on kinematic indicators, such as striae, lineations and shear fibres, are often the only data available to define the mean thrusting direction. However, although the minor structures generally provide good information about the deformation history, they can sometimes be misleading in determining the relationships between folds and thrusts when seen at map scale. Often, the shearing sense displayed by mesoscopic structures is not consistent with the map scale folds to which the minor structures are related.

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A good deal of information concerning the relationships between map scale folds and thrusts is provided by map analysis techniques: their use has been particularly successful in the study of many fold-and-thrust belts, such as the Moine Thrust Belt of NW Scotland (Elliott & Johnson 1980, Coward 1985), the Scandinavian Caledonides (Hossack 1983), the northwest external French-Swiss Alps (Butler 1985, Ramsay 1989), and the Southern Appalachian Blue Ridge province (Diegel 1986). Further information can be obtained by combining the observations on mappable features with data from structural analysis performed at the outcrop scale.

In the Umbria-Marche-Sabina Apennines (Central Italy), the relationships between the major structures which affect the sedimentary cover are particularly evident, especially in the southernmost sector of the chain. Nevertheless, in spite of the good exposure, there is to date little information about the exact orientation and continuity, both lateral and vertical, of the major folds and thrusts. Little is also known about the deformation history: the shearing sense displayed by minor structures, which is locally inconsistent with the vergence of related major folds, suggests a complex kinematic evolution.
This work aims to define the trend, geometry and evolution of major structures outcropping in the southernmost part of the Umbria-Marche-Sabina Apennines, between the Lower Nera River valley and the Rieti Basin (southeastern Umbria and northern Latium), through the use of map analysis techniques combined with observations on minor structures.

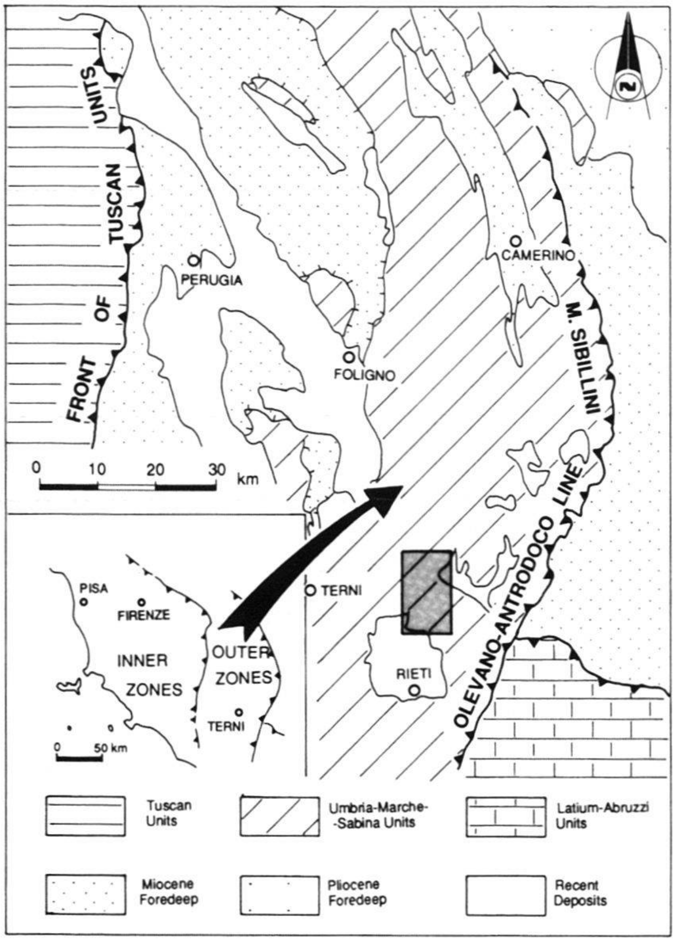


Fig. 1. Tectonic map of the Umbria-Marche-Sabina fold-and-thrust belt in the frame of the Northern Apennines (the arrow indicates the belt that occupies the outer zones of the chain). The boxed area (stippled) is illustrated in Fig. 3.

## B. Geological setting

The Umbria-Marche-Sabina Apennines occupy the outer zones of the Northern Apennines, a mountain belt which developed following the closure of the Ligurian Oceanic Domain and the collision between the Corsica-Sardinia Microplate (of European provenance) and the Insubric-Adriatic continental margin (of African provenance) during the Alpine orogenic cycle (Boccaletti et al. 1980). The chain, which extends for over 200 km, from the Marecchia Valley in the north, to the so-called "Olevano-Antrodoco" line (Salvini & Vittori 1982) in the south, outcrops between the Tuscan Units Front and the M. Sibillini Thrust Front, in the west and in the east respectively (Fig. 1). It is a classic foreland fold-and-thrust belt, Late Messinian to Early Pliocene in age, in which a sedimentary cover, made up of Late Triassic evaporites, Early Liassic-Palaeogene carbonates and Miocene foredeep deposits, is involved. In the south, the outcropping portion of the stratigraphic sequence is a mainly carbonatic multilayer, about 2500 m thick, whose Jurassic and Cretaceous-Palaeogene formations are characterized by abrupt lateral thickness variations (Fig. 2), which reflect extensive syndepositional rifting activity (Bernoulli 1967; Colacicchi et al. 1970, Centamore et al. 1971; Decandia 1982; Baldanza et al. 1982, Colacicchi & Baldanza 1986, Winter & Tapponier 1991).

The main structures within the chain are folds and thrusts, whose trend broadly defines a major arcuate feature convex towards the east (Dallan Nardi et al. 1971, Calamita & Deiana 1986, Lavecchia et al. 1988). The mean tectonic transport was towards the northeast (Coli 1981). Since Late Pliocene, the main compressional structures were affected by subsequent extensional normal faulting.

In the study of the southernmost structures, outcropping between the Lower Nera River Valley and the Rieti basin, attention has been paid to the reconstruction of individual map-scale folds and thrusts, delineated during new field mapping at 1:25000 and 1:10000 scale (Fig. 3). Particularily useful in the reconstruction of these structures and in the location of the most significant features, such as the hinge and cutoff points to be described below, were the numerous map units which could be distinguished in the upper portion of the stratigraphic sequence (Late Cretaceous-Early Oligocene Scaglia s.l.). Also very useful was the recognition, at various stratigraphic levels within the Scaglia s.l., of coarse grained limestones, whose distribution was controlled by syndepositional normal faulting of Cretaceous-Palaeogene age (Decandia 1982, Baldanza et al. 1982, Colacicchi & Baldanza 1986, Winter & Tapponier 1991).

A detailed study of a key area, based on a field mapping at 1:5000 scale (Fig. 4), allowed the complex relationships between folds and thrusts to be unravelled. The results determined by map analysis techniques will first be described, followed by data derived from the integration of structural analysis carried out at the outcrop scale, and finally an evolutionary model for the deformation which affected the sedimentary cover is proposed.

## C. Use of map analysis techniques in the study of southeastern Umbria

### *1. Fold geometry and orientation*

The continuity both lateral and vertical of the map scale folds outcropping in the investigated area has been defined in terms of axial surface trace maps (Ramsay & Huber 1987;

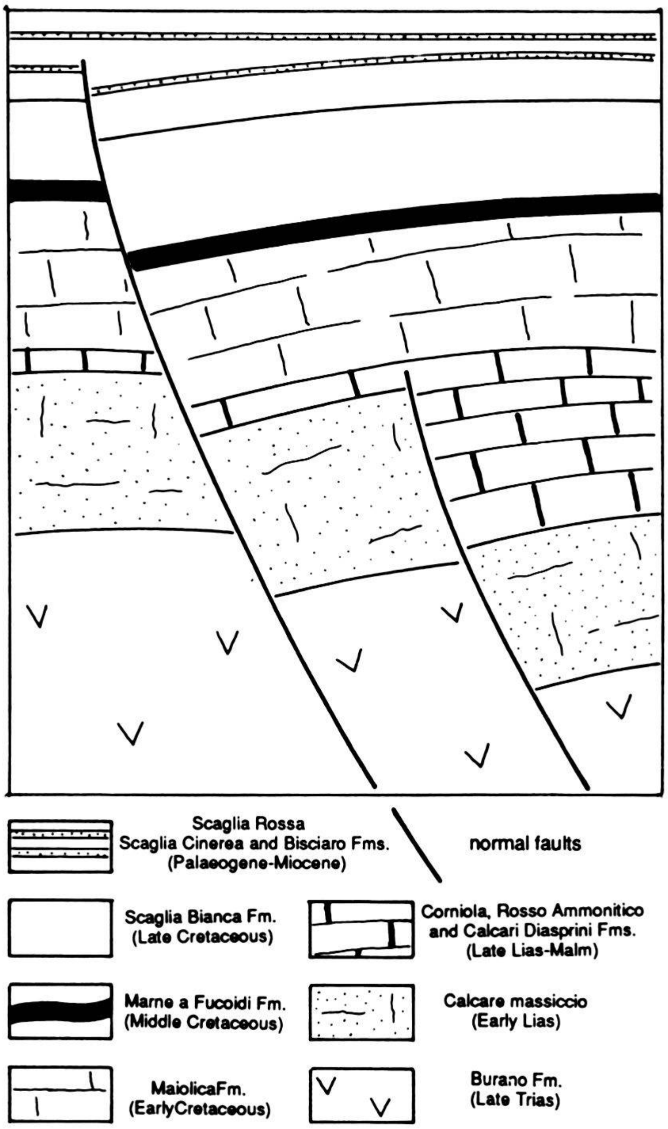


Fig. 2. Schematic stratigraphic template of the Umbria-Marche-Sabina sedimentary cover of southeastern Umbria (approximate section orientation EW). The thickness variations (not to scale), controlled by syndepositional normal faults, reflect intensive Jurassic and Cretaceous-Palaeogene rifting activity.

Ramsay 1989). The precise location of the hinge points, obtained from detailed field mapping, allows the reconstruction of the axial surface traces of individual folds (Fig. 5). Some of the major structures can be traced for over 10 km: their along strike persistence indicates that folding affected the whole outcropping portion of the sedimentary cover. However, the convergence of several traces belonging to structures only recognized in the upper stratigraphic levels and missing in the lower levels indicates the disharmonic character of folding: this is related to the presence of marly or clayey beds in the stratigraphic sequence (such as the Late Liassic Marne del M. Serrone Fm., or the Late Albian-Early Cenomanian Marne a Fucoidi Fm.), which acted as decollément horizons.

The attitude of the axial surface traces indicates that the large majority of the folds verge towards the east, consistent with the mean thrusting direction. Only locally are backward verging folds developed, especially on the western part of the investigated area. Previous studies carried out in the northern sector of the Umbria-Marche Apennines (Lavecchia et al. 1983) defined the average NW-SE orientation of the major folds

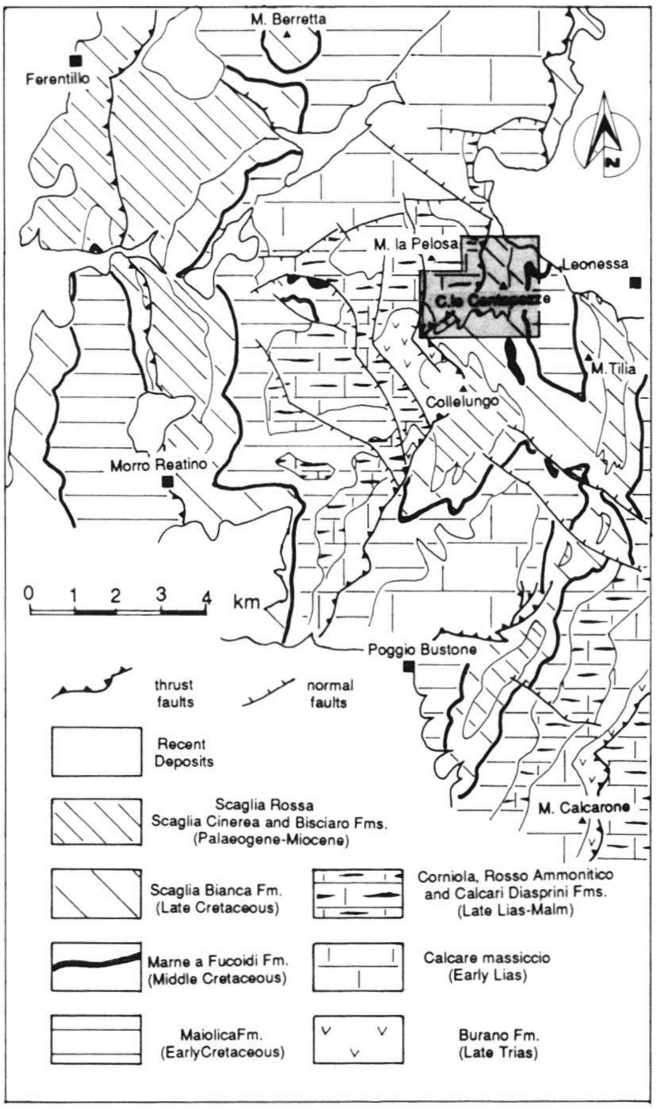


Fig. 3. Slightly simplified geological map (original field mapping at 1:25000 and 1:10000 scale) of the area between the Lower Nera River Valley and the Rieti basin (see Fig. 1 for location). The boxed area (stippled) is illustrated in Fig. 4.

by means of the π diagram method (Ramsay 1967). However, the resulting trend of map scale folds is only indicative, in that eventual along strike variations are diffucult to outline, unless the data are computed inside structurally homogeneous domains.

More accurate information about the orientation of map scale folds can be derived from the construction of hinge point tie line maps, a method described by Ramsay (1989), and first used to define the structural geometry of the Helvetic Nappes. Hinge point tie lines are straight lines connecting consecutive hinge points recognized within one and the same stratigraphic horizon: their use is effective in the definition of both orientation and space position of the hinge lines to major folds (Ramsay 1989).

A hinge point tie line map was constructed for the investigated area (Fig. 6): the hinge point tie lines generally strike NNW-SSE, and describe, in the easternmost part, an arcuate feature convex towards the east. The general parallelism between the trend of these lines and the poles obtaines with the π diagrams (Fig. 7) indicates the effectiveness of the method in defining both orientation and geographic position of the map scale fold hinge lines. The trend and dip variations displayed by the hinge point tie lines also readi-

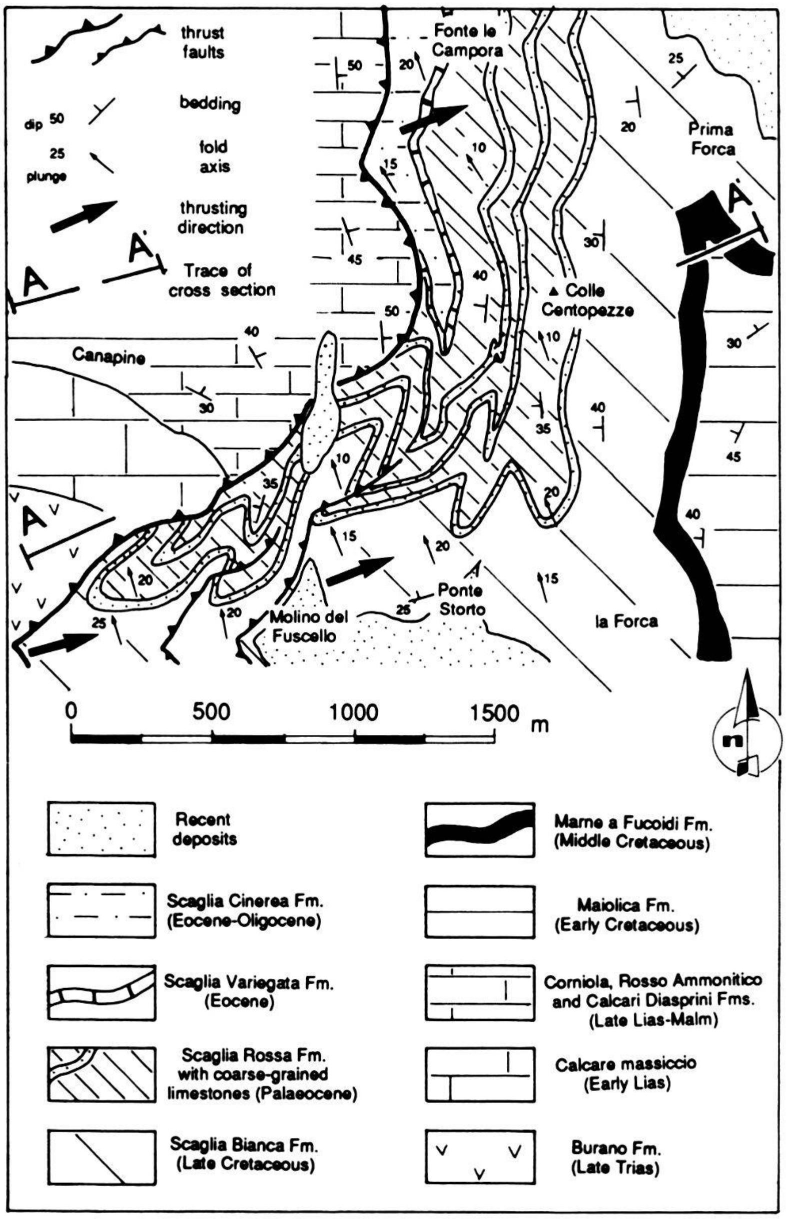


Fig. 4. Detailed geological map (original field mapping at 1:5000 scale) of the C. le Centopezze area (see Fig. 3 for location).

ly permit the location of zones in which the fold orientation is consistent (i.e. homogeneous structural domains, such as A and B in Fig. 6).

## 2. *Thrust geometry and orientation*

In the study of fold-and-thrust belts, the geometry of thrust surfaces is accurately defined by the construction of structure contour maps. However, the strike of the main thrust surfaces is also effectively expressed by the cutoff lines, whose average trend is, in turn, given by straight lines connecting adjacent cutoff points within the same stratigraphic horizon (cutoff point tie lines: Ramsay 1989). The geometry and orientation of the thrust surfaces outcropping in the investigated area has been defined in terms of a cutoff point

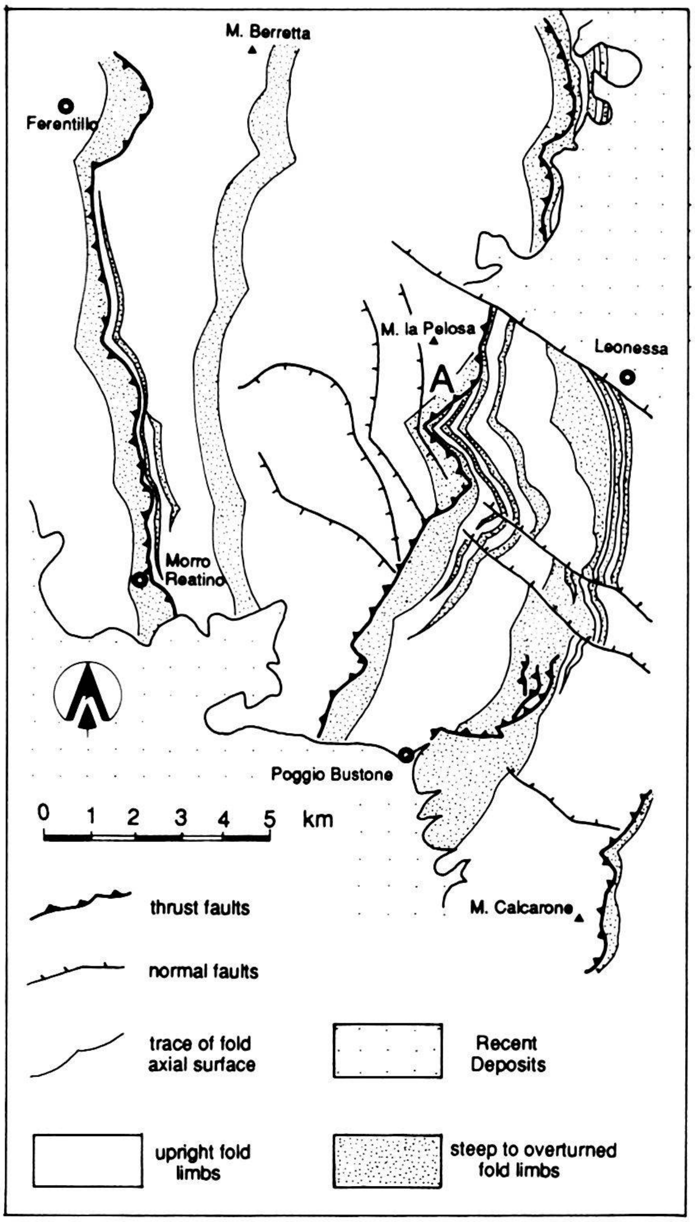


Fig. 5. Axial surface trace map of the area between the Lower Nera River Valley and the Rieti basin: the major folds display a lateral persistence for over 10 km. In A (south of M. la Pelosa) a major thrust (M. Coscerno-Rivodutri) cuts through different folds in its footwall, with local downsection trajectories.

tie line map (Fig. 6). Like the main map scale folds, the major thrusts generally trend NNW-SSE, and describe, in the easternmost part, an arcuate feature convex towards the east.

The adoption of map analysis techniques also allows the relationships between map scale folds and thrusts to be unravelled: in spite of the general parallelism between the two classes of structures, locally these relationships can be very complex. The axial traces of folds in the footwall to some important thrusts are truncated by the main tectonic surface (A in Fig. 5), indicating that the latter was preceded by development of the former. The downsection trajectory displayed by the thrust surface, also visible at the mountain side scale (Fig. 8), is characteristic for structures which experienced a complex kinematic evolution.

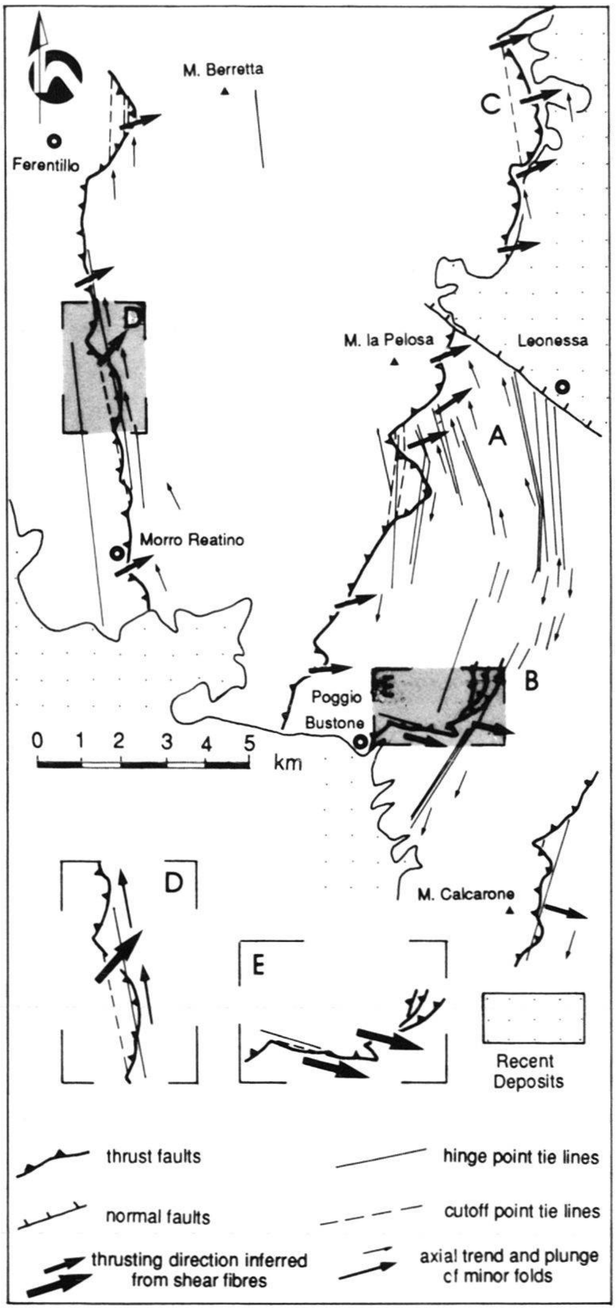


Fig. 6. Hinge point and cutoff point tie line map of the area between the Lower Nera River Valley and the Rieti basin: the major folds trend NNW-SSE, and describe an arcuate feature in the southeast. The trend and plunge variations of both major and mesoscopic folds allow two distinct, structurally homogeneous, domains (A and B) to be outlined. The striking parallelism between major folds and thrusts suggests a kinematic link between the two classes of structures: the angular relationships between the mean thrusting direction and the cutoff point tie lines indicate that thrusts evolved either in frontal (C) or oblique (D) to lateral (E) ramp situations (D and E are enlarged at the bottom of the map).

## D. Integration with minor structures

The results of structural analysis carried out at the map scale in southeastern Umbria have also been integrated with observations on minor structures: the orientation of both folds and shear fibres, measured in outcrops, is shown in Figure 6. Minor folds generally strike perpendicular or make a high angle with respect to the mean tectonic transport direction. Their axial trend is generally parallel to the hinge point tie lines, reflecting a marked parallelism between folds at all scales. The parallelism is maintained also in the southeastern sector, where the major map scale features, such as folds and thrusts, change in strike to define an arc convex towards the east.

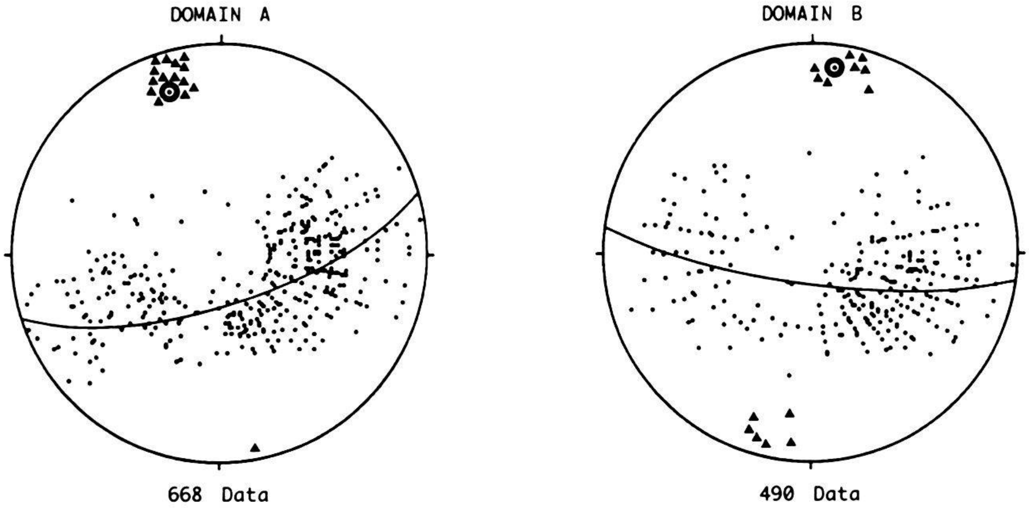


Fig. 7. Orientation of the major folds within the structurally homogeneous domains A and B of Fig. 6 (equal area stereographic projections, lower hemisphere): the dots are poles to bedding, whose best fit plunges 12° towards 007° for Domain B, and 20° towards 342° for Domain A. The general parallelism between the fold axes, as obtained with both the $\pi$ diagrams (open circles) and the hinge point tie lines (triangles), indicates the effectiveness of the latter method in defining the average fold trend and plunge.

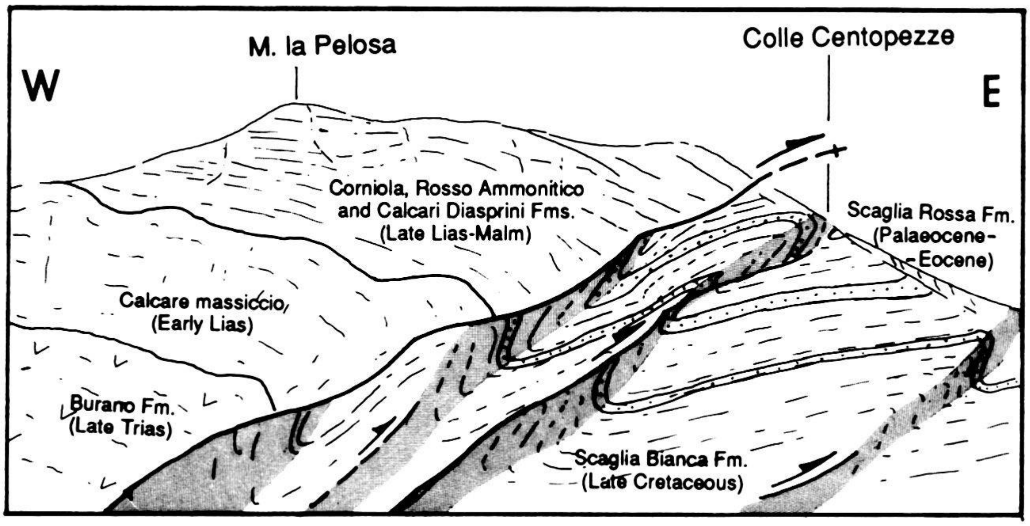


Fig. 8. The M. Coscerno-Rivodutri overthrust (view from south of M. la Pelosa, A in Fig. 5). The main thrust surface propagates through previous fold structures in the footwall with local downsection trajectories (steep to overturned fold limbs are stippled): these relationships indicate that folding preceded thrust development.

The mean tectonic transport, indicated by shear fibres measured at the base of the major thrusts, was towards the east-northeast. Only in the southeastern sector of the investigated area does the direction of the kinematic indicators rotate towards the east-southeast (Fig. 6).

The angle between the cutoff point tie lines and the mean tectonic transport is, in general, very high (i.e. close to 90°, cf. C in Fig. 6): this indicates that thrusting mainly evolved in frontal ramp situations. However, the angle between the strike of the major thrusts and the kinematic indicators locally decreases (D in Fig. 6) down to parallelism (E in Fig. 6), suggesting that thrust development also occurred in oblique and lateral ramp situations.

As previously mentioned, the strike of hinge point tie lines is generally parallel to the cutoff point tie lines, even where both features make an angle with the thrusting direction different from 90° (i.e. D and E in Fig. 6): this indicates that parallelism between the main folds and thrusts is not an exclusive condition for frontal ramp situations (Ramsay 1989), but is also to be expected for oblique or lateral ramp development.

Moreover, the general parallelism between hinge point and cutoff point tie lines suggests a kinematic link between folds and thrusts: this is confirmed by observations at the outcrop scale, where arrays of minor thrust faults affect the steep to overturned limb of asymmetric anticlines, dying out upwards. The observation that most of the map scale folds tend to concentrate in the upper stratigraphic units, and can no longer be traced in the underlying formations, also suggests that folding was a dominant process, mainly active in the upper portion of the stratigraphic template. Shortening of the sedimentary cover is therefore likely to have been accommodated by thrust-related folding, at all scales of observation: the systematic occurrence of steep to overturned synclines in the footwall to major thrusts suggests an origin related to fault-propagation folding (Williams & Chapman 1983, Suppe 1985, Jamison 1987, Suppe & Medwedeff 1990, Mitra 1991).

## E. History of deformation

The results derived from the combination of both map and outcrop scale structures provide a key for interpreting the processes active in shortening the sedimentary cover. The deformation history recorded by minor structures in response to fault-propagation folding is expected to be relatively simple. However, very often in the umbro-marchean Apennines the shearing sense displayed by these structures is not consistent with the major folds in which they are involved (Lavecchia et al. 1983, Decandia & Tavarnelli 1990): this implies a complex kinematic evolution.

The Collelungo syncline (see Fig. 3 for location), a major eastward verging fold in the footwall to an important overthrust, offers numerous examples of downward facing minor structures (Fig. 9): these are generally mesoscopic folds, locally associated with thrust faults, which affect the Middle Cretaceous Marne a Fucoidi Fm, and do not propagate through the underlying stratigraphic units. The systematic eastward vergence of these minor folds on the overturned limb of the main syncline is not consistent with the shearing sense expected for flexural slip mechanisms. These relationships indicate that regional folding was preceded by the development of eastward verging mesoscopic structures. The general, striking parallelism between folds at all scales (Fig. 6), suggests the folding, though developed at different times, was coaxial.

Both folds and thrusts observed in outcrop on the overturned limb of the Collelungo syncline are affected by later extensional faults (A in Fig. 9) whose striae (B in Fig. 9) are consistent with the mean thrusting direction (C in Fig. 9). These normal faults, closely spaced at the base of the major thrust fault, are gently dipping towards the east: they can therefore be interpreted as synthetic features inside a shear zone developed in the advanced stages of thrusting.

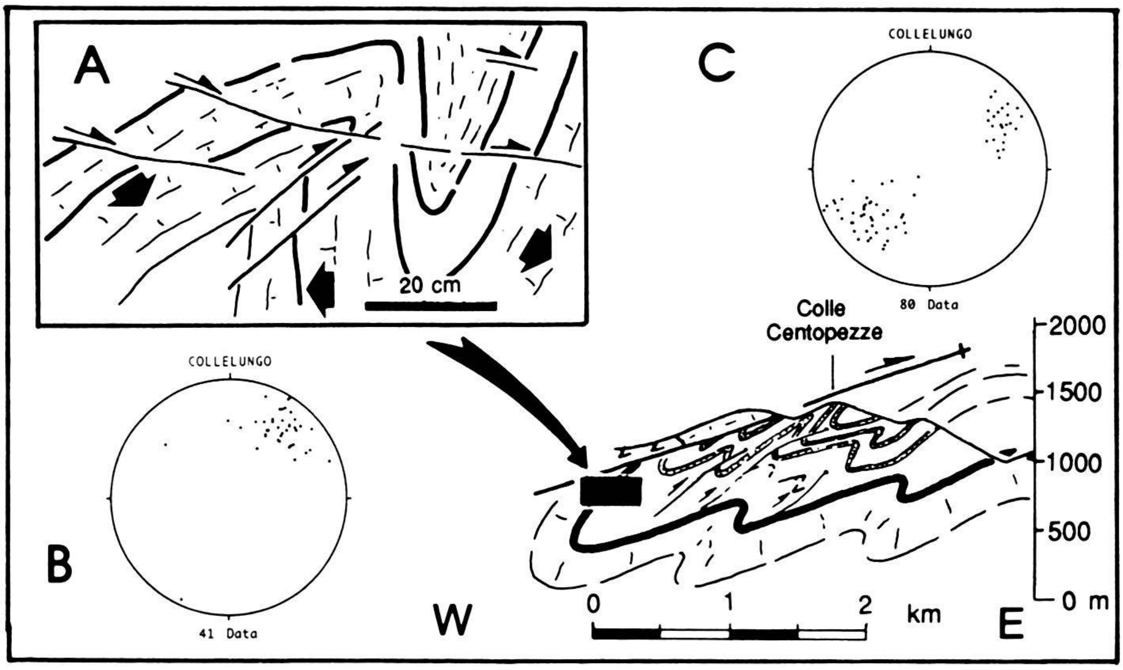


Fig. 9. Cross section across the Collelungo Syncline (trace of section A-A' in Fig. 4), in the footwall to the M. Coscerno-Rivodutri overthrust (symbols as in Fig. 2). The overturned limb of the syncline contains downward facing thrust-related minor folds, affected by late extensional features (A), whose kinematic indicators (B) are consistent with the mean tectonic transport direction measured at the base of the thrust (C).

A – Mesoscopic downward facing folds affected by late extensional features (the large arrows indicate the stratigraphic way-up). B – Mechanical striae and calcite fibres on the normal faults affecting the downward facing minor folds (the spherical mean azimuth is 42°). C – Mechanical striae and calcite fibres on the shearing surfaces at the base of the thrust (the spherical mean azimuth is 46°).

The complex structural evolution of the Collelungo syncline can be taken as a model to describe the deformation history of the sedimentary cover in the southernmost Umbria-Marche-Sabina Apennines as a whole. This can be summarized as follows (Fig. 10): A– initially only the upper portion of the sedimentary cover is affected by thrusting: during this stage eastward verging minor structures develop in the stratigraphically intermediate to high clayey or marly levels within the subhorizontal sequence, which act as decollément horizons; B– subsequently, a major pair of asymmetric folds, coaxial with the previous minor structures, develops at the termination of a deeper thrust tip, in response to fault-propagation folding which affects the whole sedimentary cover; C– finally, the major thrust breaks through the steep to overturned limb of the asymmetric folds and truncates the previous decollement; thrusting is accompanied by the development of a wide shear zone and associated synthetic extensional features: these affect all the previous minor structures.

The presence of downward facing minor structures could result from the activation of upper glide horizons (flats) progressively higher in the stratigraphic template, as deformation procedes eastwards. This interpretation accounts for the locally observed complex relationships between folds and reverse faults in the footwall to the major thrust surfaces (A in Fig. 5, see also Fig. 8). The activation of upper flats, progressively higher with-

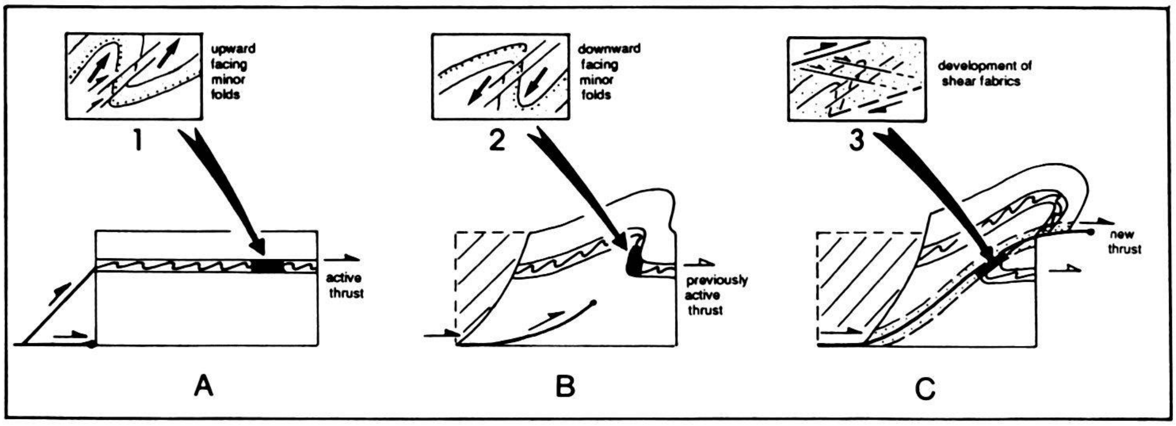


Fig. 10. Structural evolution of the Collelungo Syncline for simple breaching of a linked-thrust system: A – development of upward facing minor folds (1) due to the activation of a decollément within the stratigraphic template; B – development of thrust-related map scale folds, whose overturned limbs contain previous minor structures, now downward facing (2); C – upward propagation of a new thrust, whose upper flat is located in a higher stratigraphic, and subsequent truncation (breaching) of the previously active decollément; thrust evolution is accompained by thickening of the shear zone, whose fabrics affect all the previous minor structures (3).

in the stratigraphic template, due to footwall collapse and to the consequent development of new thrust surfaces climbing up through older, previously active thrusts (Fig. 10), implies a structural evolution for breaching within a linked-thrust system (Butler 1987): this complex evolution is a variant of piggy-back, foreland-propagating thrusting sequences. A piggy-back deformation sequence is consistent also with the observed thrusting patterns: the radial distribution of the kinematic indicators (Fig. 6), in fact, does not necessarily reflect a real radial thrusting pattern, but could instead be related to the foreland-directed migration of the whole thrust system, with older thrusts and associated shearing fabrics refolded and reoriented by development of new structures in their footwall (Tavarnelli 1993). A deformation history for breaching is in good agreement, not only with the structural data, as described above, but also with the stratigraphic evolution of the northern Apennines: this indicates the progressive eastward migration of the foredeep basins (Ricci Lucchi 1986). Moreover, breaching seems likely to have occurred, based on the observation that in the investigated area the main thrust sheets are superimposed on the Late Eocene-Early Oligocene Scaglia Cinerea Fm., while, further towards the east, they directely lie on the Messinian to Early Pliocene Laga Flysch (Koopman 1983, Lavecchia 1985, Cooper & Burbi 1986).

However, although the cited evidence, both structural and stratigraphic, is consistent with a deformation evolution for breaching, a possible role of Jurassic and Cretaceous-Palaeogene syndepositional normal faults in producing the aforementioned complexities during the Neogene compression cannot be excluded.

## F. Conclusions

The results obtained by applying map analysis techniques to the structures affecting the sedimentary cover in the southernmost Umbria-Marche-Sabina Apennines indicate:

a there is marked parallelism between folds at all scales (even in the case of non-coeval structures) inside the homogeneous structural domains defined by the hinge point tie lines, which affirms the effectiveness of the methodology in determining the trend and geographic position of the map scale fold hinge lines;
b there is general parallelism between folds and thrusts at ramps, not only frontal but also lateral and oblique ramps, which implies a kinematic link between the two classes of structures;
c the relationships between folds and thrusts examined at the map scale indicate that shortening of the sedimentary cover was accommodated by thrust-related folding (more precisely, fault-propagation folding).

These results, integrated with observations on mesoscopic structures, are helpful in reconstructing the deformation history. The Neogene structural evolution, though very complex when seen in detail, can be explained in terms of simple breaching, in the framework of a general foreland-directed progressive deformation. However, the role of both Jurassic and Cretaceous-Palaeogene normal faults cannot be excluded in determining the complexities displayed by the Neogene compressional features.

Map analysis techniques therefore represent a useful tool to determine the orientation and geographic position of the major structures found in fold-and-thrust belts; their use, combined with observations on mesoscopic structures, provides a key for reconstructing the deformation history, which, in turn, is essential in correct cross section construction and in the consequent estimate of the amount of orogenic contraction.

## Acknowledgments

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