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Relationships between Mesozoic extensional tectonics, stratigraphy and Alpine inversion in the Southern Alps

By Carlo Doglioni [1])

ABSTRACT

The eastern Southern Alps have been used as regional example for a few considerations about the relationships between extensional tectonics, horizontal and vertical lithological facies changes, and Alpine (Southalpine and Dinaric) inversion. Some paleostructures may be identified by structural undulations in the thrust belts. They occur above inherited synsedimentary normal faults, facies- and thickness variations. Several physical parameters are controlling the final inversion structure. The orientation of the direction of compression with respect to the pre-existing normal faults and lateral facies changes are of fundamental importance. For example, high angle normal faults dipping in a direction opposite to that of the thrust plane are difficult to be reactivated, whilst normal faults dipping in the same direction or within a few degrees with respect to the thrust plane are more easily inverted by transpression or compression. Normal faults or facies boundaries striking perpendicular to later thrusts often induce undulations and transfer zones in the belt. Sequence boundaries and transgressive systems tracts are the best stratigraphic horizons for decollements.

RIASSUNTO

Le Alpi Meridionali orientali sono prese come esempio regionale per alcune considerazioni generali sulle relazioni tra tettonica distensiva, variazioni litologiche e di facies sia orizzontali che verticali, e inversione alpina (Sudalpina e Dinarica). Alcune paleostrutture possono essere identificate da ondulazioni strutturali nella catena di sovrascorrimenti, poiché queste avvengono sopra faglie normali sinsedimentarie ereditate, o variazioni di facies e di spessore. Numerosi parametri fisici controllano la struttura finale. In particolare viene qui considerata l'influenza dell'orientazione della compressione rispetto alle faglie normali pre-esistenti e delle facies coinvolte. Per esempio faglie normali ad alto angolo immergenti nella direzione opposta al piano di sovrascorrimento sono difficilmente riattivate, mentre faglie normali immergenti nella stessa direzione e con pochi gradi rispetto al piano di sovrascorrimento sono più facilmente invertite in transpressione o compressione. Faglie normali o limiti di facies con direzione perpendicolare a sovrascorrimenti successivi sono spesso sede di ondulazioni nella catena e zone di trasferimento. I limiti e i tratti trasgressivi delle sequenze deposizionali sono i livelli preferiti di scollamento.

Introduction

The main interest of this paper is to propose some considerations about the relationships between Mesozoic extensional or transtensional tectonics, stratigraphy and Alpine compression or transpression. The relationship between tectonics and stratigraphy is a very widespread topic. It involves the control operated by differential subsidence in the thickness, facies and areal development of sedimentary sequences; the interplay between tectonics and eustatic cycles; the influence of the stratigraphic-paleotectonic architec-

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ture during later collisional processes. Platform to basin transitions and other lithologic contrasts control fault positioning and vice-versa. This paper will mainly deal with the influence of inherited paleotectonic and stratigraphic features on Alpine inversion. Thrust belt reconstructions have to take into account the articulated geometries of the upper crust, due to pre-existing tectonics and/or lateral facies changes, particularly in the sedimentary cover. This discussion is based on field evidence from the eastern Southern Alps, in particular Dolomites and Venetian Prealps (Fig. 1), which show excellent exam-

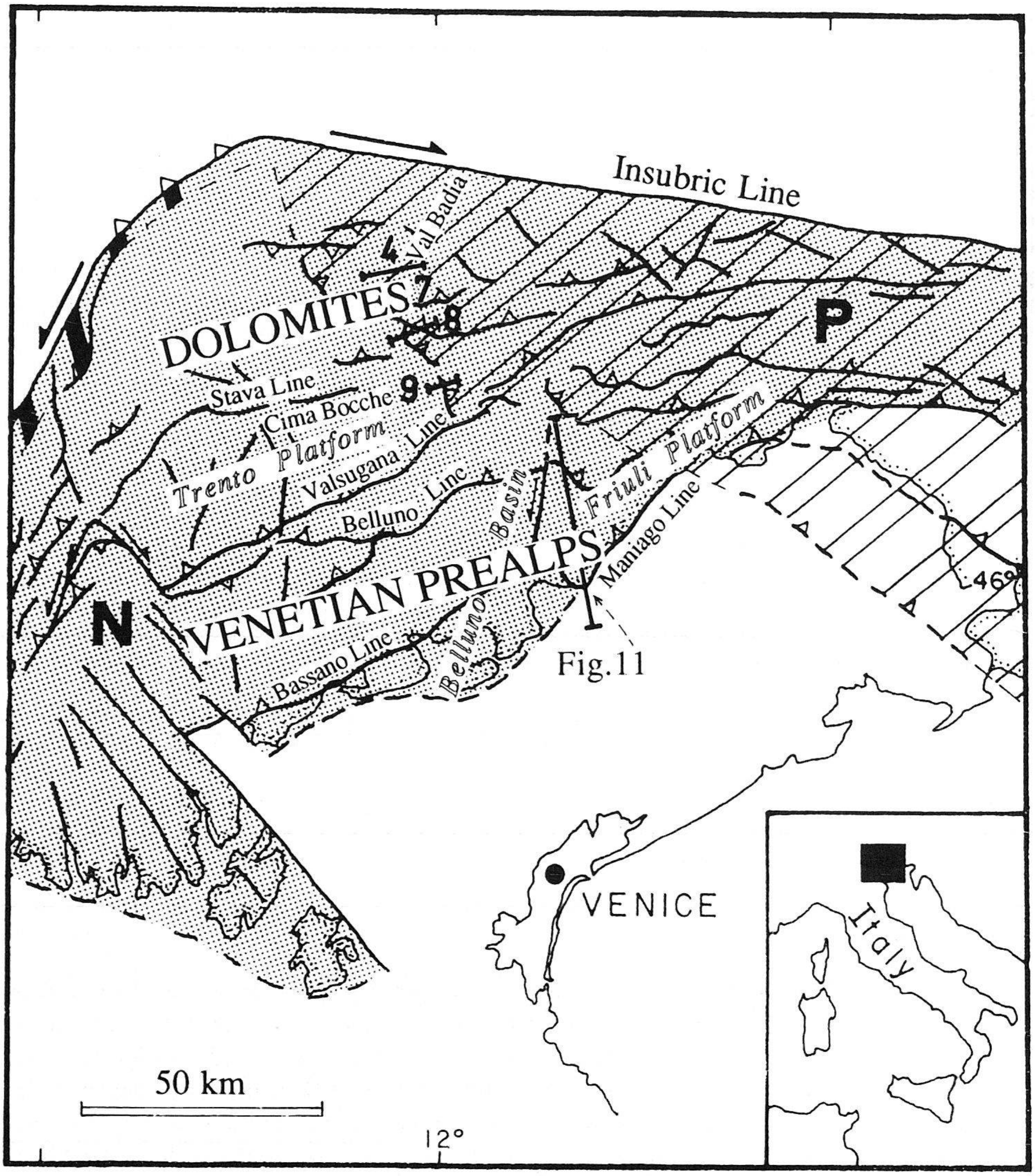

Fig. 1. Location map. P: WSW-vergent Paleogene-Early Neogene Dinaric thrust belt. N (shadow): SSE-vergent Late Paleogene-Neogene Southalpine thrust belt. Note the interference area between the two thrust belts in the east. Numbers refer to following figures.

ples of the relationship between tectonics (both Mesozoic synsedimentary and Alpine inversion) and stratigraphy.

Geological setting

The Southern Alps are part of a Mesozoic passive continental margin broken into N–S trending horsts and grabens (Bernoulli 1964, Castellarin 1972, Bosellini 1973, Bernoulli et al. 1979, Winterer & Bosellini 1981). The stratigraphic evidence for Mesozoic crustal stretching has been confirmed by structural analysis (Brodie & Rutter 1987, Handy 1987, Bertotti 1990). Late Permian – Early Cretaceous crustal thinning has been documented by several authors in different parts of the Southern Alps (Castellarin 1982, AA.VV. 1986, Doglioni & Bosellini 1987, Bernoulli et al. 1990, Castellarin & Picotti 1990). The Southern Alps were located in the northern part of the Adriatic plate during the rifting stages, close to a major E–W trending transform zone where sinistral transtensional movements may have occurred (Trümpy 1982, Weissert & Bernoulli 1985). In the Southern Alps the extension was not cylindric and several transfer zones accommodated lateral offset of grabens. The basin and swell configuration of the Southern Alps was inherited by the Alpine Late Cretaceous – Late Tertiary compression, induced by the dextral transpression along the Insubric Line (Laubscher 1983, Schmid et al. 1989). In fact the thrust belt undulates along these inherited features (Bosellini 1965a). The Southern Alps are a classic thrust belt (Laubscher 1985) which represents the backthrusted part of the Alpine edifice. The N 0° – 30° W compression obliquely inverted the N–S trending Mesozoic features. In a section across the Dolomites and the Venetian Prealps, the Southern Alps show a conservative shortening of 40–50 km (Doglioni 1987, 1991). The sedimentary cover of the Dolomites has been shortened during the Paleogene time by the WSW-directed Dinaric phase by at least 10–15 km. These features have been inherited by the SSE-directed Southalpine phase which in the Venetian Prealps mainly ranges in age between Late Oligocene and Quaternary times. Tortonian sandstones are thrust by the Valsugana Line (Venzo 1939) and Pliocene shales are folded (Venzo 1977) along the frontal triangle zone. Moreover Messinian-Pliocene onlap geometries on the southern border of the chain mainly support a Neogene age of the deformation (Massari et al. 1986).

Synsedimentary tectonics and lateral facies changes

The crust of the Dolomites and the Venetian Prealps underwent stretching throughout the major part of the Mesozoic. The extension generated generally N–S trending normal faults (Figs. 2 and 3) and N 70°–90° E transfer faults. The extension may be considered to result from sinistral transtension, the Southern Alps being close to the northern transform margin of the Adriatic plate. In this view, the grabens are en-échelon features, or pull-aparts. Elongated and localized structures (faults and folds) probably due to sinistral Middle Triassic transpressive tectonics can be detected in the alignment of the Stava Line with the Cima Bocche Anticline. This alignment runs about N 70°–90° E across the Dolomites and is cut by Late Ladinian volcanics in the Predazzo and Monzoni centers (Doglioni 1984). During Ladinian time, the anomalous and strong tectonic phase was coeval with a general subsidence operating in the Dolomites with

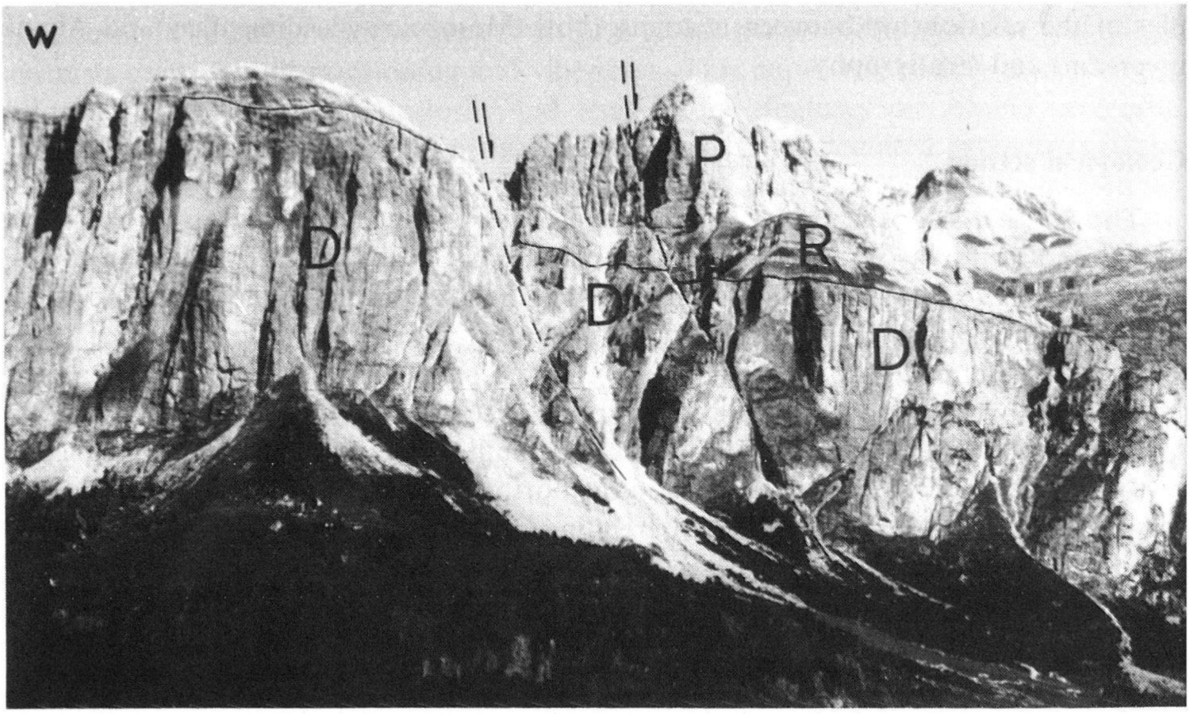

Fig. 2. N–S trending, E-dipping normal faults above Colfosco (Corvara in Badia, central-northern Dolomites, between M. Cir and Sassongher) with a slightly listric shape, in the Puez-Gardenaccia Massif. Compare Fig. 4. Legend: P, Dolomia Principale (Norian); R, Dürrenstein Dolomite or Raibl Formation (Late Carnian); D, Upper Cassian Dolomite (Middle Carnian). The normal faults often show reddish oxidized cataclasites and sometimes neptunian dikes. The Liassic age of the faults is interpreted on the basis of regional considerations, spacing between normal faults, attitude and the synsedimentary evidences of the normal fault shown as Fig. 3.

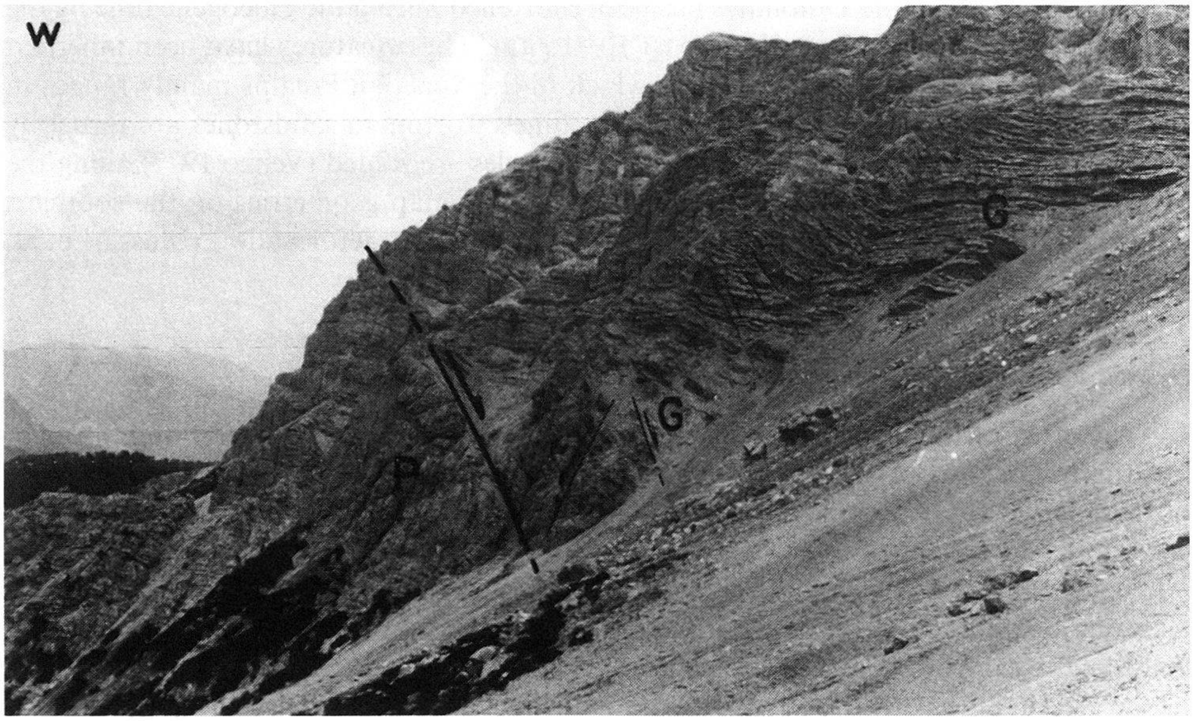

Fig. 3. N 10° W-trending, E-dipping normal fault in the western cliff of the M. Lavarella. Liassic Calcari Grigi (G) in the hangingwall exhibit a fan geometry suggesting growth movement along the fault. P, Dolomia Principale (Norian). Compare Fig. 4.

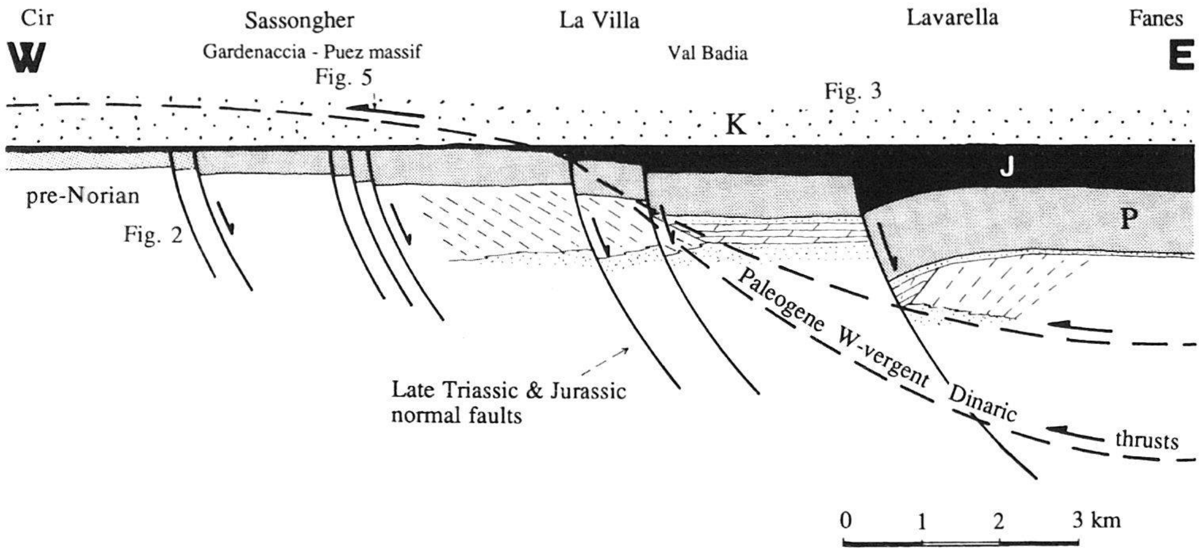

Fig. 4. Schematic pre-inversion E–W section between the Gardenaccia-Puez Massif to the left, through the Val Badia in the middle, to the Fanes plateau to the right. Regularly spaced N–S trending, E-dipping normal faults of at least Late-Triassic-Liassic age characterize the area. This is supported by eastward increase of thicknesses of formations. The area represents the hinge zone between the Trento "Horst" to the left and the Belluno "Graben" to the right. Note that the W-vergent dinaric thrusts inherited this architecture and used the main lateral weakness zone as a ramp. P, Dolomia Principale; J, Jurassic, (Calcari Grigi outcropping only in the eastern part of the section); K, Puez Marls, Cretaceous.

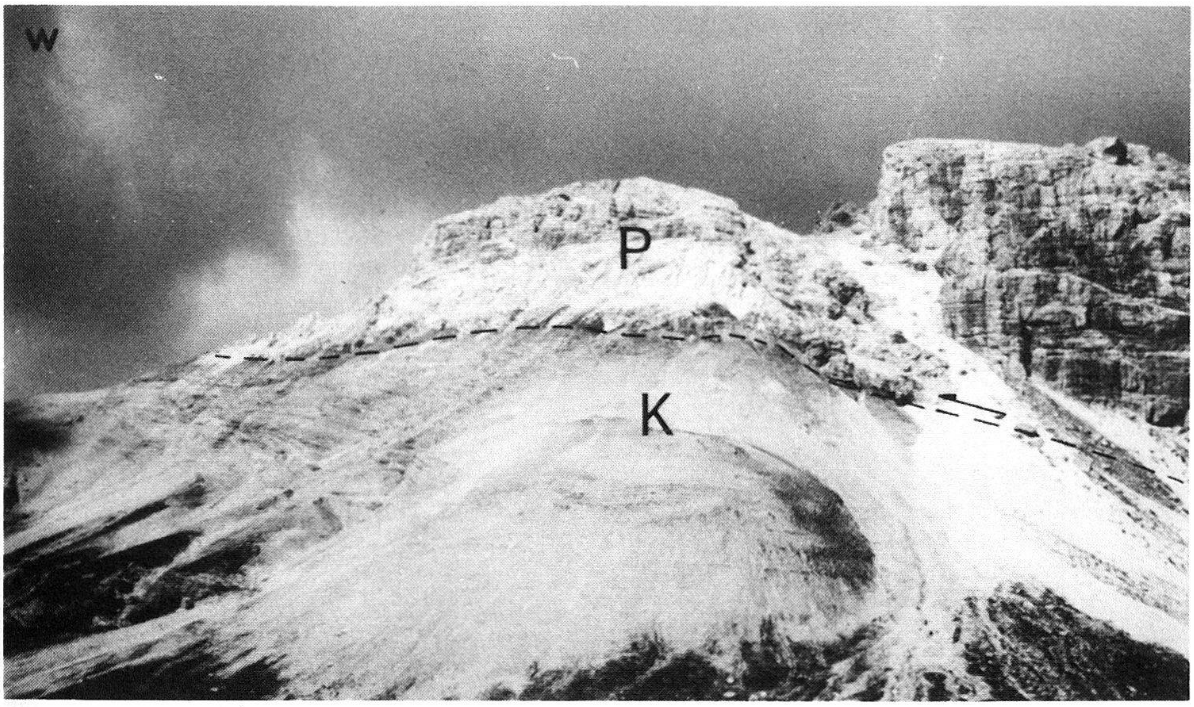

Fig. 5. The Puez thrust, with Norian Dolomia Principale (P) in the hangingwall and the Lower Cretaceous Puez Marls (K) in the strongly sheared footwall. Puez Massif, central-northern Dolomites. The thrust is almost flat and it is WSW-directed, Paleogene in age, and belonging to the Dinaric thrust belt front. Compare Fig. 4.

different subsidence rates in different areas. This partly controlled the growth of carbonate platforms with different thicknesses, morphologies and internal geometries (Doglioni et al. 1989). Synsedimentary N–S trending normal faults may be seen in several parts of the region, and their activity is interpreted for Anisian, Ladinian, Carnian, Liassic and Early Cretaceous times (see Bosellini 1965b, 1968, Doglioni & Neri 1988, Doglioni 1990, 1991, and references therein). Clear examples are located at the margin between the Trento Platform and the Belluno Basin (Bosellini 1965b, Bosellini & Doglioni 1986). This hinge zone is present also in Val Badia, northern Dolomites, where 500 m of Jurassic Calcari Grigi occur at the eastern margin, whilst to the west this formation is absent (Figs. 2, 3, and 4). The transition has been inherited by the later W-directed Paleogene Dinaric compression which used it as a major ramp (Figs. 4 and 5).

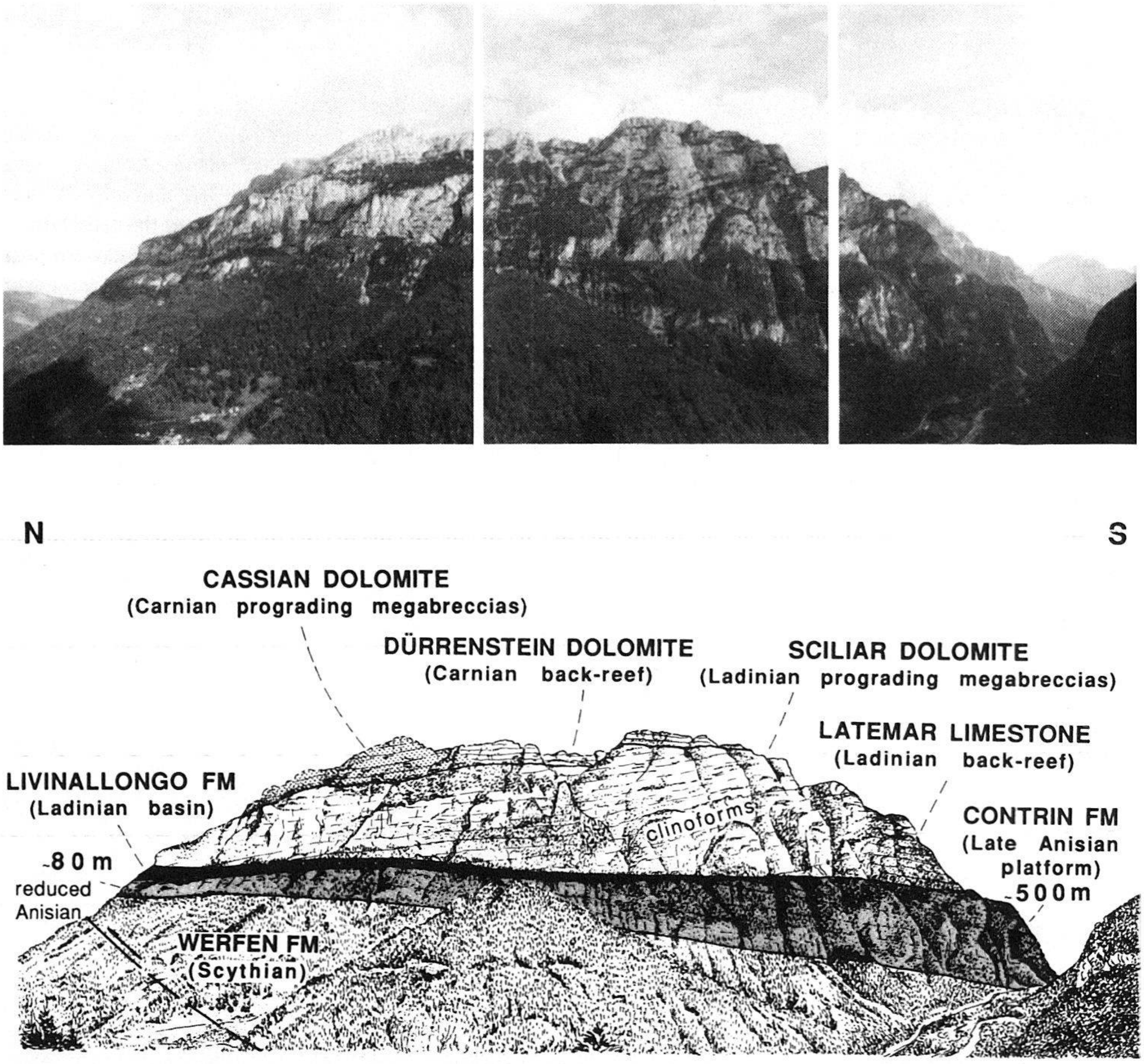

Fig. 6. View onto the Monte Alto di Pelsa, western part of the Civetta Massif in the central Dolomites. Note the extreme lateral variation of thicknesses and facies along the cliffs. This architecture gives an example of the significant lateral variations of the sedimentary cover which have been inherited by tectonics in other complicated areas. The thrust on the left occurred at the platform-basin transition and transported the platform sequence over the basinal one. View from locality Martin, westward above Cencenighe Agordino. See Fig. 8 for location.

Frequent lateral facies and thickness variations are well known in the Dolomites where spectacular platform to basin transitions are observable (Mojsisovics 1879, Leonardi 1967, Bosellini 1984). Fig. 6 shows an example at a "seismic scale" in the Civetta Group (Busatta 1991), in a not too intensly deformed natural section. In transtensive realms there usually are short and more articulated structures and facies developments when compared to pure tensional environments. The irregular, "not-layer-cake" geometry of the sedimentary cover of the region controlled the morphology of shortening. For a review of the stratigraphy of the region see Winterer & Bosellini (1981), Gaetani et al. (1981), Brandner & Mostler (1982), Blendinger (1983), Bosellini (1984), Massari et al. (1986), Bosellini & Doglioni (1988), Goldhammer et al. (1990), Masetti et al. (1991), and references therein.

Alpine inversion

Alpine tectonics inherited the complicated Mesozoic features. This is clearly observable in the Venetian Prealps where the structural undulations of the thrust belt are strongly controlled by the Mesozoic basin and swell configuration: transpressive or transfer zones are all located on top of pre-existing anisotropies (Doglioni 1991). In general, in the Southern Alps, N–S trending, E-dipping Mesozoic normal faults have been cut and involved in the thrust belt without major reactivations. In fact they are the easiest normal faults to observe in the field (Figs. 2 and 3). See the examples of Froitzheim (1988) and Froitzheim & Eberli (1990) for the eastern Alps. Instead W-dipping Mesozoic normal faults are very often deformed and reused by sinistral transpression. The best case is the Giudicarie Belt, representing the biggest Alpine undulation due

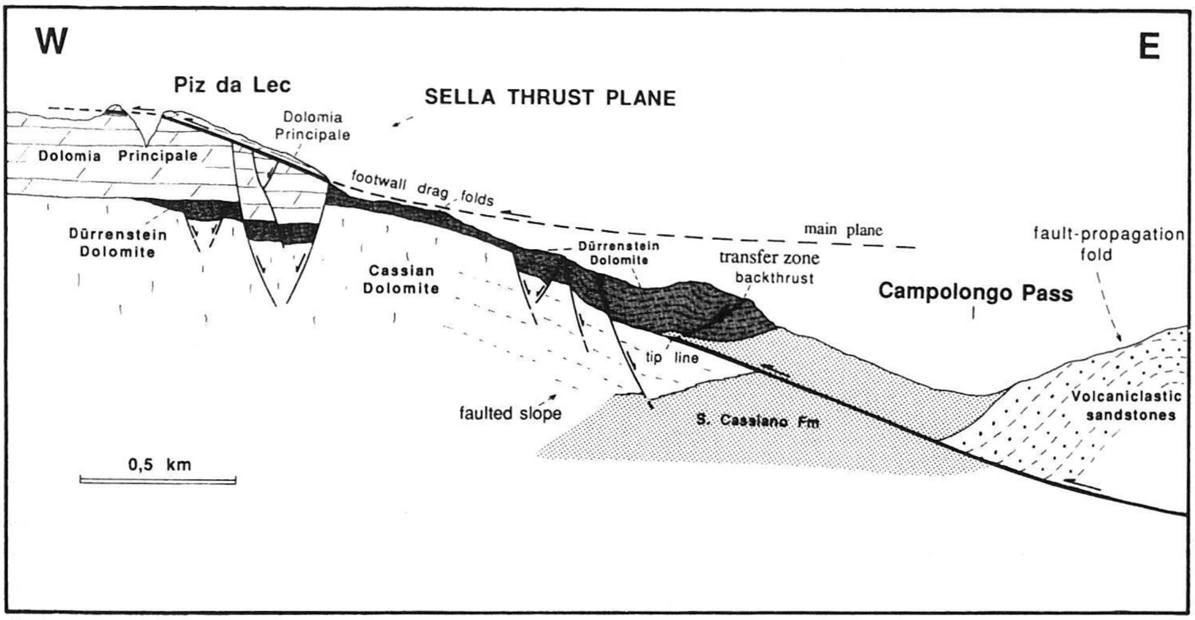

Fig. 7. Section of the eastern flank of the Sella Massif, central Dolomites. The W-directed Paleogene Dinaric thrust partly used the E-dipping slope of the Middle Carnian Cassian Dolomite as a ramp. N–S trending Late Carnian and later normal faults complicate the section. See insert map of Fig. 8 for location.

to sinistral transpression: it occurred at the W-dipping margin between the Trento Platform to the east and the Lombard Basin to the west. Sometimes inherited N–S trending normal faults may be simply translated or folded by Alpine compression, without major reactivation. High angle (60°–90°) normal faults are usually cut in depth by low angle (0°–30°) thrust planes. Very often they are sligthly moved by horizontal shear, the polyphase tectonics beeing testified by both vertical and younger horizontal striations on the fault plane.

Thrusts may occur on limbs and clinoforms of carbonate platforms. These represent strong anisotropies in the sedimentary cover and may have concentrated stresses. Fig. 7 is an example where a thrust emplaced near the slope of the Carnian isolated carbonate platform of the Sella massif, in the central Dolomites (modified after Doglioni 1985). Undulations of the thrust planes (oblique and lateral ramps) often occur at platform margins. Decollements are typical in basinal and evaporitic sequences. Sequence boundaries and transgressive systems tracts are also good sites for decollement layers (Doglioni 1985, 1988, 1990). The Dolomites are obliquely cross-cut by the front of the Dinaric thrust belt. This compression is responsible for the "summit overthrusts" of the Dolomites, spectacular isolated klippen (Accordi 1955, Colacicchi 1960, Doglioni 1985),

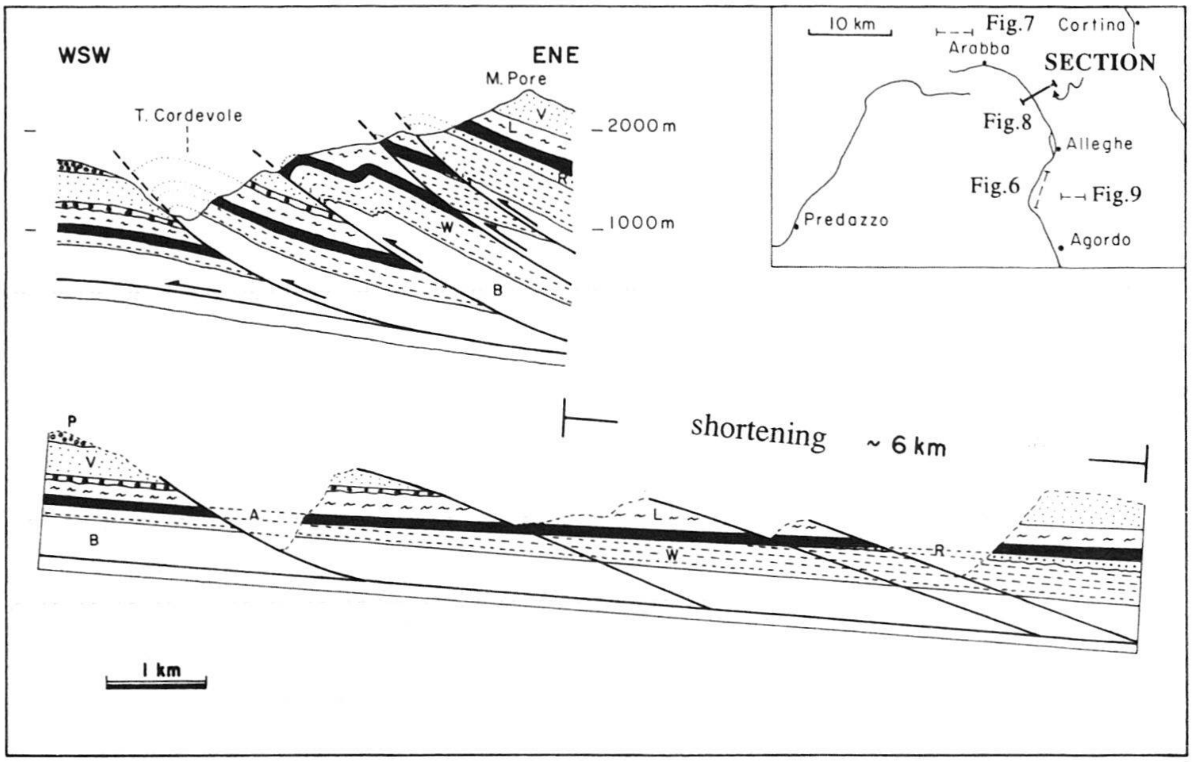

Fig. 8. Balanced cross-section of the front of the Dinaric thrust belt in the central Dolomites, between M. Pore and Digonera. The thrusts exhibit an imbricate fan geometry, with main decollement plane in the evaporitic Late Permian Bellerophon Formation (B). Shortening is about 6 km. The present stacking shows different thicknesses especially of the Werfen Formation (W) in the different thrust sheets: after retrodeformation of the section the Werfen Formation is more complete and thicker to the east, due to a minor Late Anisian erosion, covered by the Richthofen Conglomerate (R). Anisian limestones (A); Livinallongo Formation and Zoppè Sandstones (L); Volcaniclastic sandstones with at the base interbedded levels of Caotico eterogeneo (V); pillow-lavas (P).

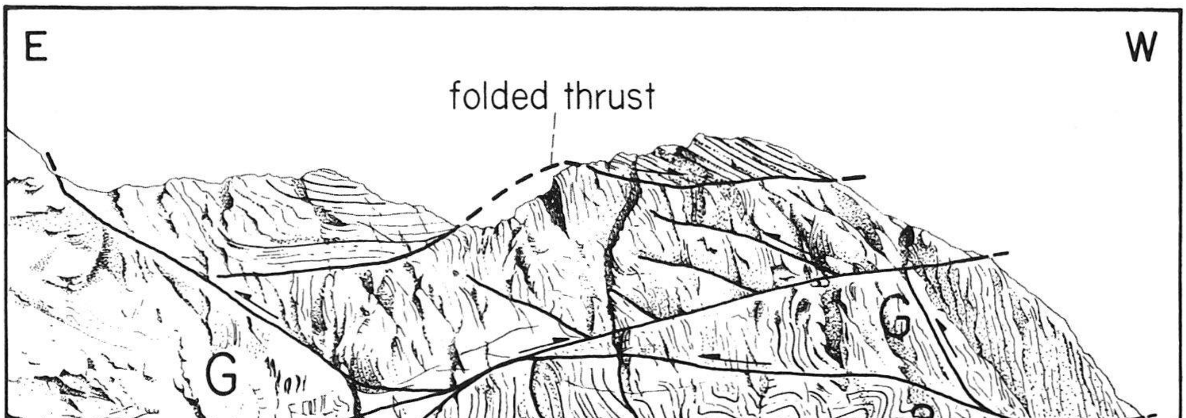

Fig. 9. Examples of triangle zones in the Civetta Massif (Van dei Sass, central Dolomites). Numbers indicate the kinematic progression of the triangles. Front of the W-vergent Paleogene Dinaric thrust belt. G, Liassic Calcari Grigi.

and for the WSW-directed thrusts observable in several parts of the region, preserved in spite of the later SSE-directed Southalpine compression. The Dinaric thrust belt in the Dolomites (Fig. 8) shows an imbricate fan geometry (Boyer & Elliott 1982), with the main decollement level seated in the Late Permian evaporitic Bellerophon Formation. The retrodeformation of this section shows how the in sequence progression of the thrust sheets was progressively involving sections with westward increase of the Anisian erosion. In the Dolomites the Dinaric thrusts flatten when they enter the Cretaceous Puez Marls (Fig. 4), inverting or passively cutting pre-existing normal faults. The Dinaric phase is responsible for the main deformation of the sedimentary cover of the Dolomites. This deformation has later been perpendicularly cross-cut by the Southalpine tectonics (Doglioni & Siorpaes 1990). The front of the Dinaric thrust belt moves southeastward in the Friuli region, without affecting the Venetian Prealps, which have been deformed only by the Southalpine SSE-directed thrusting (Fig. 1).

The fronts of the Dinarides and of the Southern Alps are characterized by frequent triangle zones (Fig. 9). The triangle features are more frequent in basinal sequences, or in well bedded platform sequences, or at the inversion of paleofaults where strong lithologic contrasts facilitated wedging. Fault-propagation folding (Fig. 10) and fault-

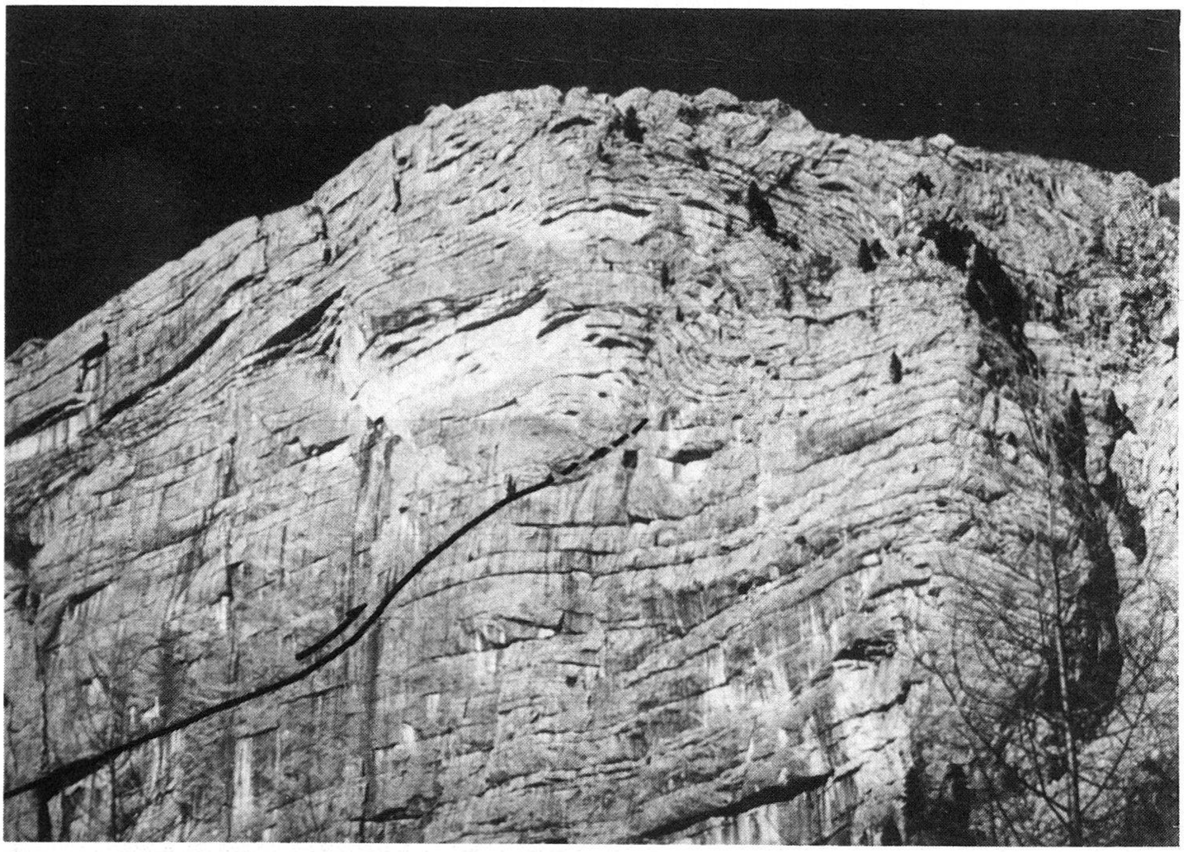

Fig. 10. Example of fault-propagation folding in the Liassic Calcari Grigi, northern flank of the Vallon Bianco Valley, north of Cortina d'Ampezzo. Note how the displacement of the fault is decreasing along the ramp, and is adsorbed by folding in the upper part. This is allowed by the peculiar rheology of the Calcari Grigi which are easily folded due to thin marly interbedded supratidal levels permitting flexural slip. The cliff is about 50 m high. Northeast to the right.

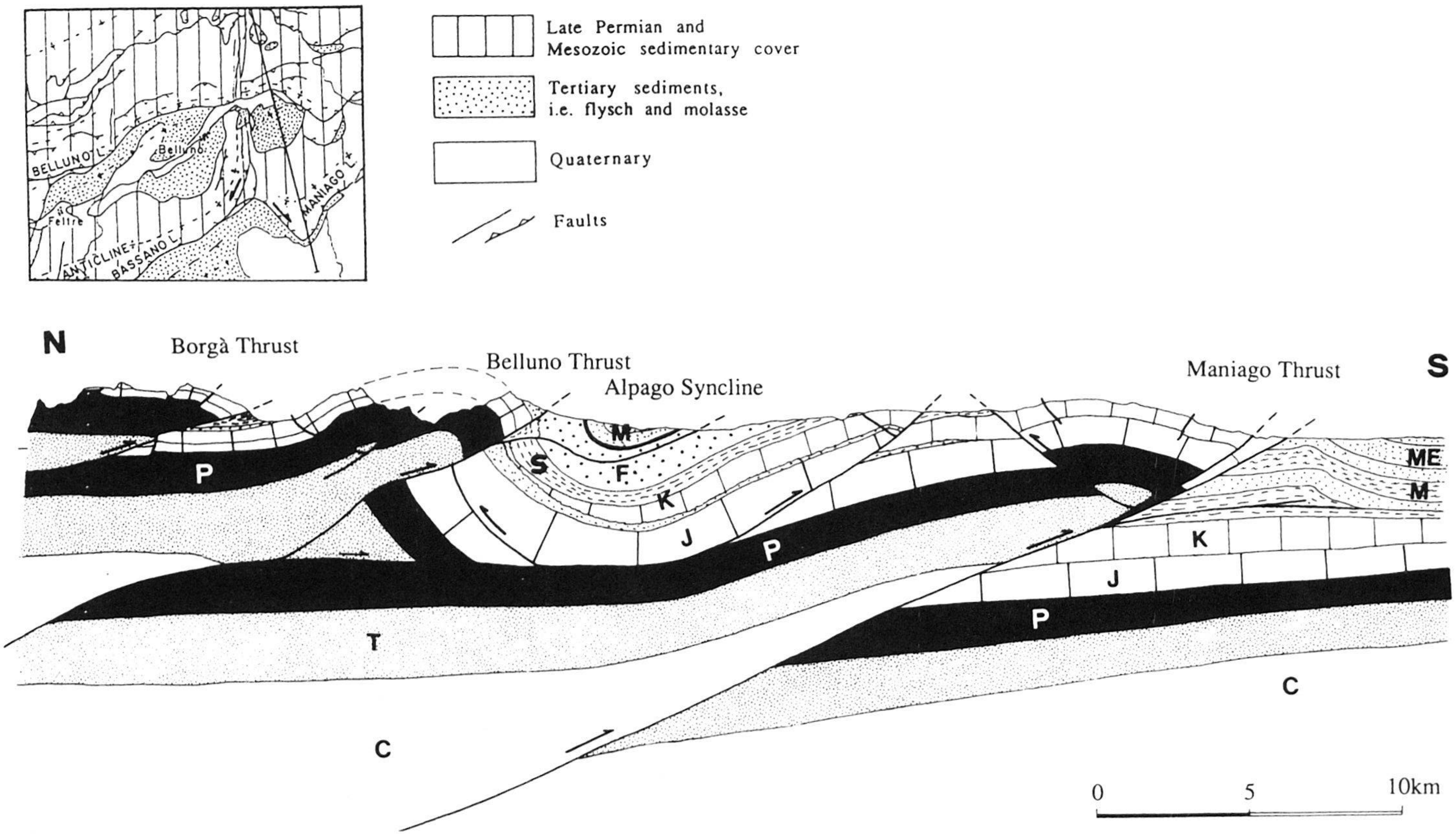

Fig. 11. Cross-section of the eastern Venetian Prealps. The Belluno Thrust emplaced at the margin between the Belluno Basin sequence (in the hangingwall) and the Friuli Platform sequence (in the footwall). Legend: C, undifferentiated crystalline basement; T, Late Permian and Early-Middle Triassic formations; P, Late Triassic Dolomia Principale; J, undifferentiated Jurassic: platform facies (Calcari Grigi) in the southern part of the section, gradually passing northward to basinal facies (Soverzene Formation, Igne Formation, Vajont Limestone, Fonzaso Formation, Ammonitico Rosso); K, Cretaceous, platform facies (Calcare del Monte Cavallo) gradually passing northward to slope deposits and basinal facies (Calcare di Soccher, Biancone); S, Scaglia Rossa, Late Cretaceous – Paleocene; F, Eocene Flysch; M, Late Oligocene – Early-Middle Miocene Molasse; ME, Messinian conglomerates.

bend folding (Suppe 1983, Mitra 1988, Mitra & Namson 1989 and Suppe & Medwedeff 1990) are the most typical mechanisms of imbrication and shortening in the region.

The section shown in Fig. 11 is positioned at the transition between the sequence of the Friuli Platform in the south (Ferasin 1958) and the Belluno Basin in the nothern part (Riva et al. 1990). The Belluno Thrust brings the basinal sequence over the platform sequence.

Inversion modelling

The importance of the inherited mechanical properties of the crust in controlling later deformational processes is of crucial importance (Laubscher 1967, 1972). Tectonic inversion has been documented in several ways (Bally 1984, Cooper & Williams 1989, Butler 1989, De Graciansky et al. 1989, Hayward & Graham 1989, McClay 1989, Letouzey et al. 1990). The 3D reconstruction remains an open problem of inversion structures. Inversion is usually considered in two dimensions, i.e. a graben later inverted into a pop-up. However the direction of later compression is not always parallel to the direction of stretching. The Southern Alps for instance, as we said before, have been inverted with an angle of about 20°–40° between the direction of pre-existing grabens and the Alpine

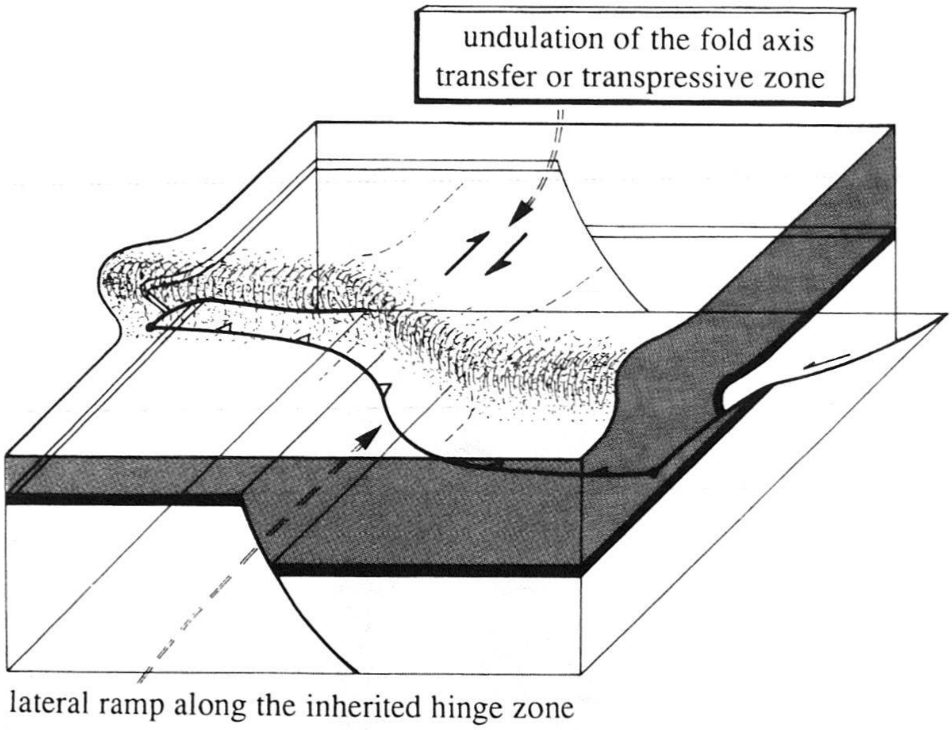

Fig. 12. Undulations of fold axis and thrust plane reflect the presence of paleostructures (i.e. normal faults or facies changes) in depth. The undulation of the fault-propagation fold will be a function of the angle of compression with respect to the buried feature. Between 0° and 30°–40°, there are the strongest undulations. The drawing represents the case of 0°, with compression parallel to the pre-existing normal fault. Lateral ramp forms along the inherited anisotropy.

maximum stress. In the Jura mountains Laubscher (1972) pointed out the importance of the interference angle between Oligocene Rhine graben-related normal faults and the later Neogene compression.

A pre-existing synsedimentary normal fault in the upper crust of a given region represents a strong anisotropy of the body, both for the different thicknesses and possible lithologies in the footwall and in the hangingwall of the normal fault (Fig. 12). Moreover the normal fault may represent a natural weakness zone in which deformation can concentrate during basin inversion. The presence of structural undulations of the fold axis may then be a good indicator of buried anisotropies, normal faults and/or facies changes (compare Figs. 4 and 5 of Doglioni 1991). From surface structural data we can therefore predict the possible presence of paleostructures or lateral rheological variations in depth only by undulations, which are witnesses of deep lateral ramps and transfer zones (Fig. 12). We often observe significative structural difference in style of imbrication above the two walls of the inherited normal fault, i.e. on one side an imbricate fan, whilst the shortening is expressed by a major backthrust on the other side.

The later compression may have any angle with respect to the normal fault trend (Fig. 13): all these factors, direction of inversion, thickness and rheologic gradients, amount and type of inherited extension, the P-T-t conditions, are parameters controlling the style of inversion, which may be very articulated and different in any given situation. Normal faults may be folded and reused by flexural slip during later compression, as proposed for the Lugano Line by Bertotti (1990). Actual inversion of normal faults occurs when peculiar conditions are respected, i.e. low angle between thrust plane and pre-existing normal fault, both in direction and dip. Fig. 13 shows a few examples of position of the thrust plane with respect to the pre-existing normal faulting, $-90°$, $-45°$, $0°$, $45°$, $90°$. The $-90°$ is the case in which the normal fault dips in the opposite direction with respect to the thrust plane. In this case no significant structural undulation forms. The normal fault is cut and only eventually may be reactivated as a backthrust. The range between $-45°$, $0°$ and $45°$ is the span of angles in which it is possible to observe the greatest structural undulations and lateral ramps of the thrust plane as it intersects the normal fault. In the $90°$ case pure inversion may occur (compression parallel to the pre-existing extension) if the normal fault dips with an angle close to the dip angle of the thrust plane and may partly be reactivated as a frontal ramp.

As we mentioned before, thrusting in the Dolomites has affected platform-basin margins oriented perpendicularly to the compression axis: this produced rising of basinal facies along the slopes (Fig. 7). The case in which compression is parallel to the platform-basin margin is discussed in Fig. 14. Basinal sediments usually cause less inclined ramps than carbonate platform rocks. Two stratigraphic sections of the same thickness, one with basinal sediments in the upper half part and the second one with an entire carbonate section will be cross-cut by a thrust with different angles. This should result in a longer ramp of the plane throughout the carbonate platform with respect to the basinal section, and this produces different levels of flats which are also not aligned along strike (higher and more external for the carbonate section). Two coeval but displaced fault-bend folds should form: the more external one on top of the carbonate platform sequence. Transfer zones and lateral ramps develop at the transition between the two structural styles. This may be applied to the Venetian Prealps front: see the schematic map of Fig. 11 in which the anticline in the hangingwall of the Maniago Thrust is more external (Cansiglio area,

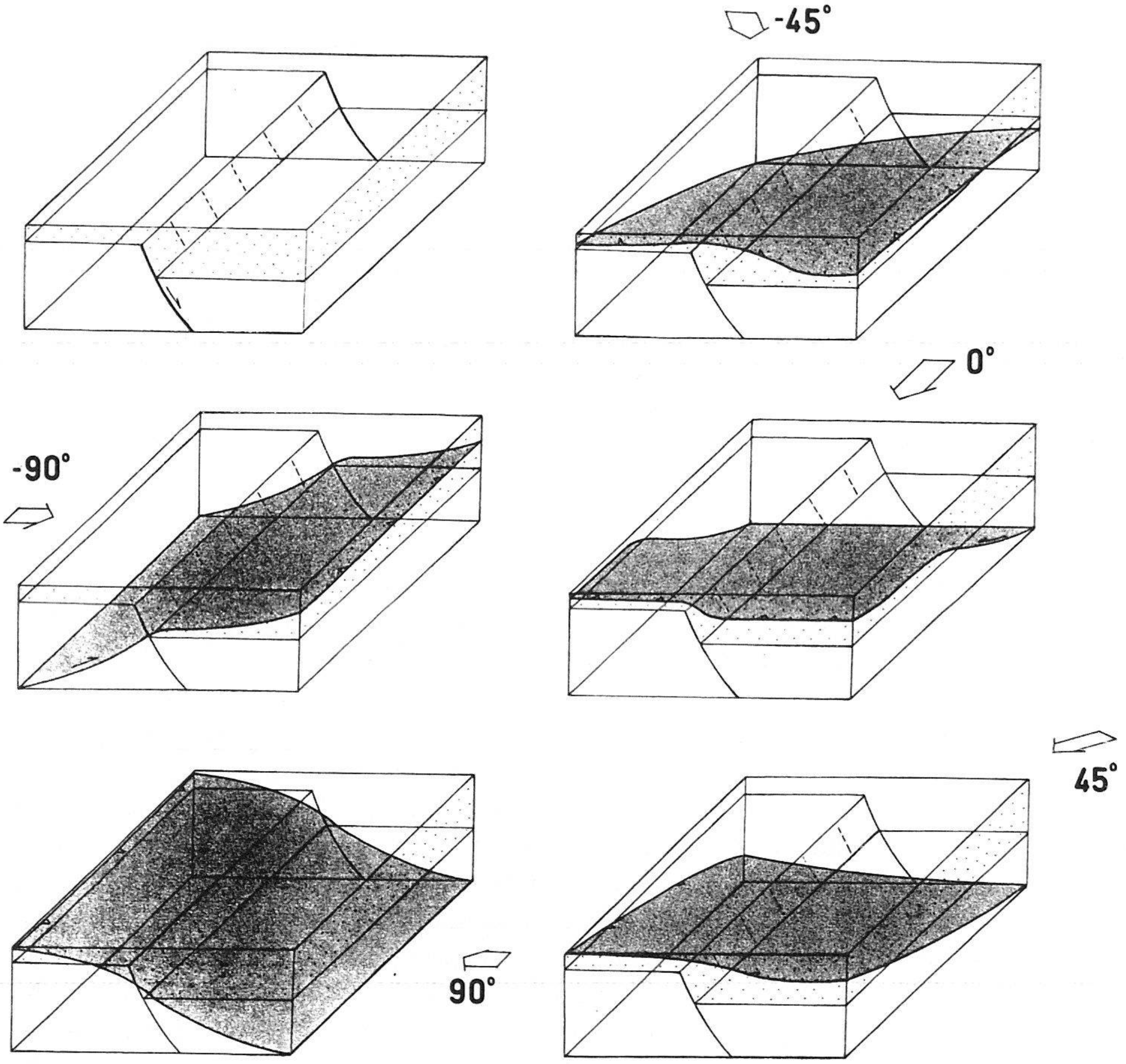

Fig. 13. A synsedimentary normal fault may be compressed at any angle. The normal fault represents the boundary between two bodies with sometimes strong rheologic differences, and the fault plane itself can represent a strong anisotropy of the crust. Reactivation (inversion) of pre-existing faults is controlled by the angle of compression with respect to the inherited fault, the relative angles of dip and by the rheology of the rocks of the footwall and of the hangingwall. A −90° compression can for instance cross-cut the paleostructure, without major inversion; sometimes minor backthrusting may occur. Major inversions develop when the paleostructure dips in a direction close to the direction of the thrust plane and when there is a small angle between the two planes (90°). Lateral and oblique ramps are frequent close to buried pre-existing normal faults intersected at oblique or perpendicular angles (−45°, 0°, 45°).

Friuli Platform sequence) than the anticline in the hangingwall of the Bassano Thrust (Visentin area, Belluno Basin sequence).

The compression of a platform-basin system may produce irregular patterns as a function of the angle of compression with respect to the trend of the margin between the two realms. The regional example of the Venetian Alps shows for instance that the SSE-directed Southalpine thrusts obliquely cut the pre-existing margin between the

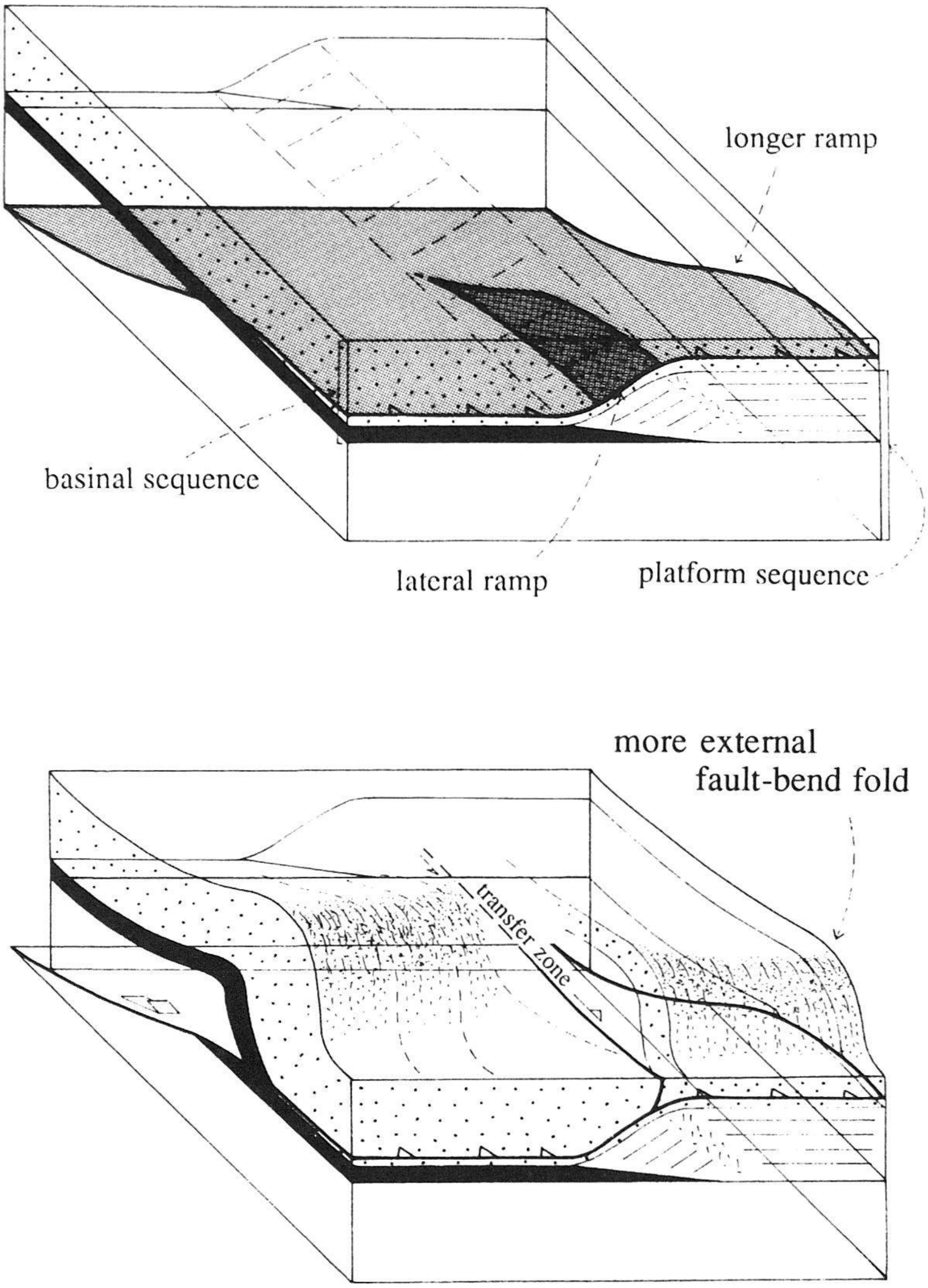

Fig. 14. A compression perpendicularly affecting a platform-basin margin will produce different lengths of the ramp plane due to the differences in the shear angle between carbonate platform sequences (longer ramp, right section) and shaly basinal sequences (shorter ramp, left section). The lower part of the section is considered as homogeneous with similar ramp angles in both sections. The upper part is differentiated in a basinal-platform system. The flat in the platform sequence will occur at the very top of the carbonate section in a more external position and consequently the fault-bend fold will be more advanced with respect to the coeval, more internal fault-bend fold located in the basinal section. A transfer zone at the platform-basin margin will allow this structural undulation, with a lateral ramp of the main thrust plane. This configuration could be applied to the western margin of the Friuli Platform, where the Cansiglio Anticline in the hangingwall of the Maniago Thrust, cutting a Mesozoic platform sequence, is more external with respect to the M. Grappa-Visentin Anticline in the hangingwall of the Bassano Thrust, deforming the Jurassic-Cretaceous sequence of the Belluno Basin (compare Fig. 11).

Trento Platform and the Belluno Basin sequences (Fig. 15, compare Fig. 5 of Doglioni 1991). The margin is actually quite irregular and it is diffused in an area of some tens of km if we consider the horst (structural concept of platform) and the facies (paleogeographic concept of platform) as a migrating hinge: i.e. tectonically retrograding or sedimentologically prograding platform margin. The compression of a platform-basin paleogeographic architecture may produce thrusting of one facies onto the other and vice-versa. The northern margin of the Friuli Platform for instance has been overridden by the Belluno Basin sequences due to the Belluno Thrust. Along the Belluno Thrust we observe a dextral apparent displacement between platform facies in the haningwall and basinal facies in the footwall: this may be explained with an oblique thrusting of the platform-basin transition. This may enable us to predict buried basinal facies beneath platform facies in the footwall of some thrust sheets (Fig. 15) and to quantify the amount of shortening if the offset is not due to original transfer zones.

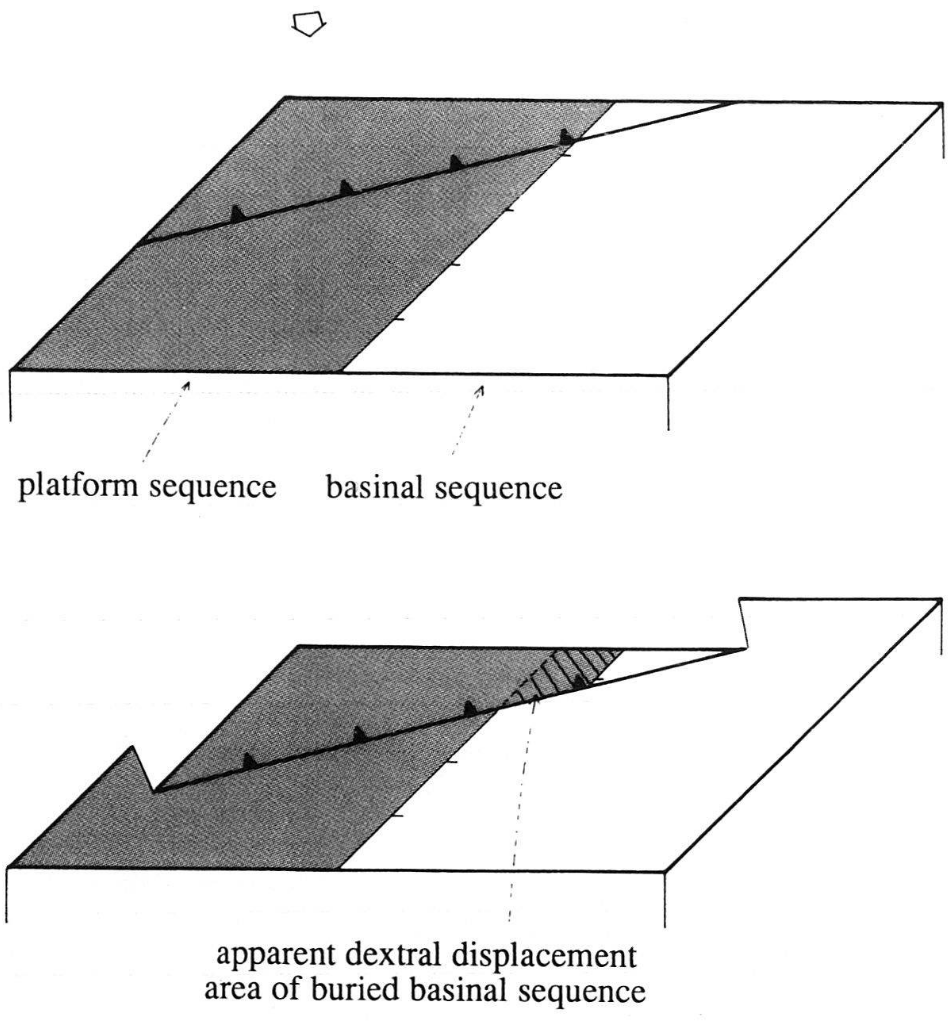

Fig. 15. A thrust obliquely affecting a platform-basin margin will produce an apparent dextral displacement. For instance the Trento Platform was thrust towards southeast over the Belluno Basin in the Venetian Prealps, due to the southalpine N 20°–30° W compression oblique to the Mesozoic N–S trending margin.

The irregular rheology of the sedimentary cover is reflected in the staircase trajectories of the thrust planes. Within basement synclines the sedimentary cover was mainly detached at the Bellerophon Formation level, allowing flexural slip. The contrast between the sedimentary cover, where flexural slip is facilitated by shaly or other incompetent layers, and the basement, where the irregular foliations and granites inhibit flexural slip, enhances the structural difference of the two bodies. This may result in "out-of-sequence" thrusting (Fig. 16) for instance along the Valsugana Line where the

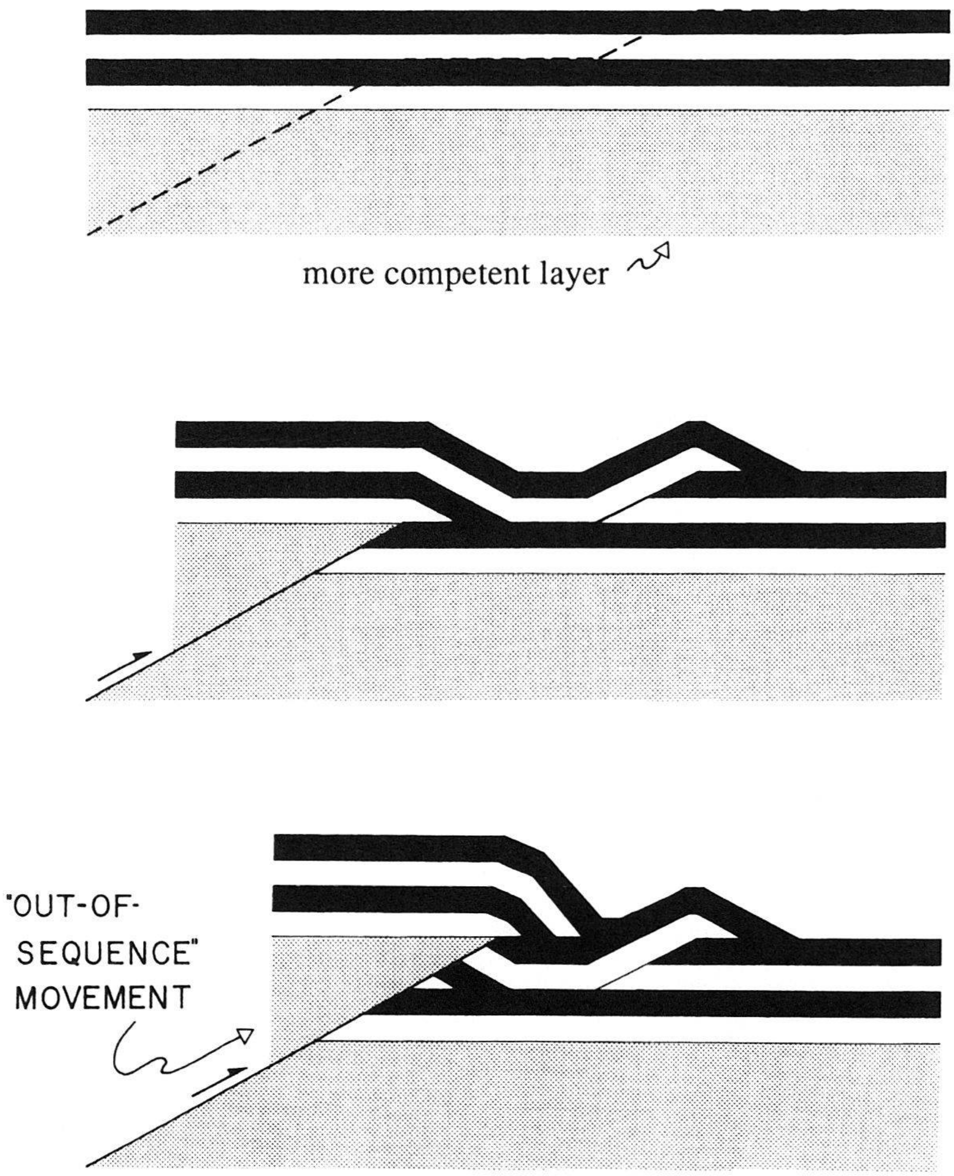

Fig. 16. Example for the dependence of thrust trajectory and fold development on rheological layering. Ramp-flat geometries occur when for instance in the sedimentary cover lithologic contrasts exist. Fault-bend folding is also controlled by the possibility of folding through flexural slip of a package of rocks. If a more competent layer (i.e. the crystalline basement) cannot be folded at superficial P–T conditions, when it arrives at the top of the ramp, it may continue to move upward in ramp abandoning the earlier staircase trajectory, producing an "out-of sequence" movement.

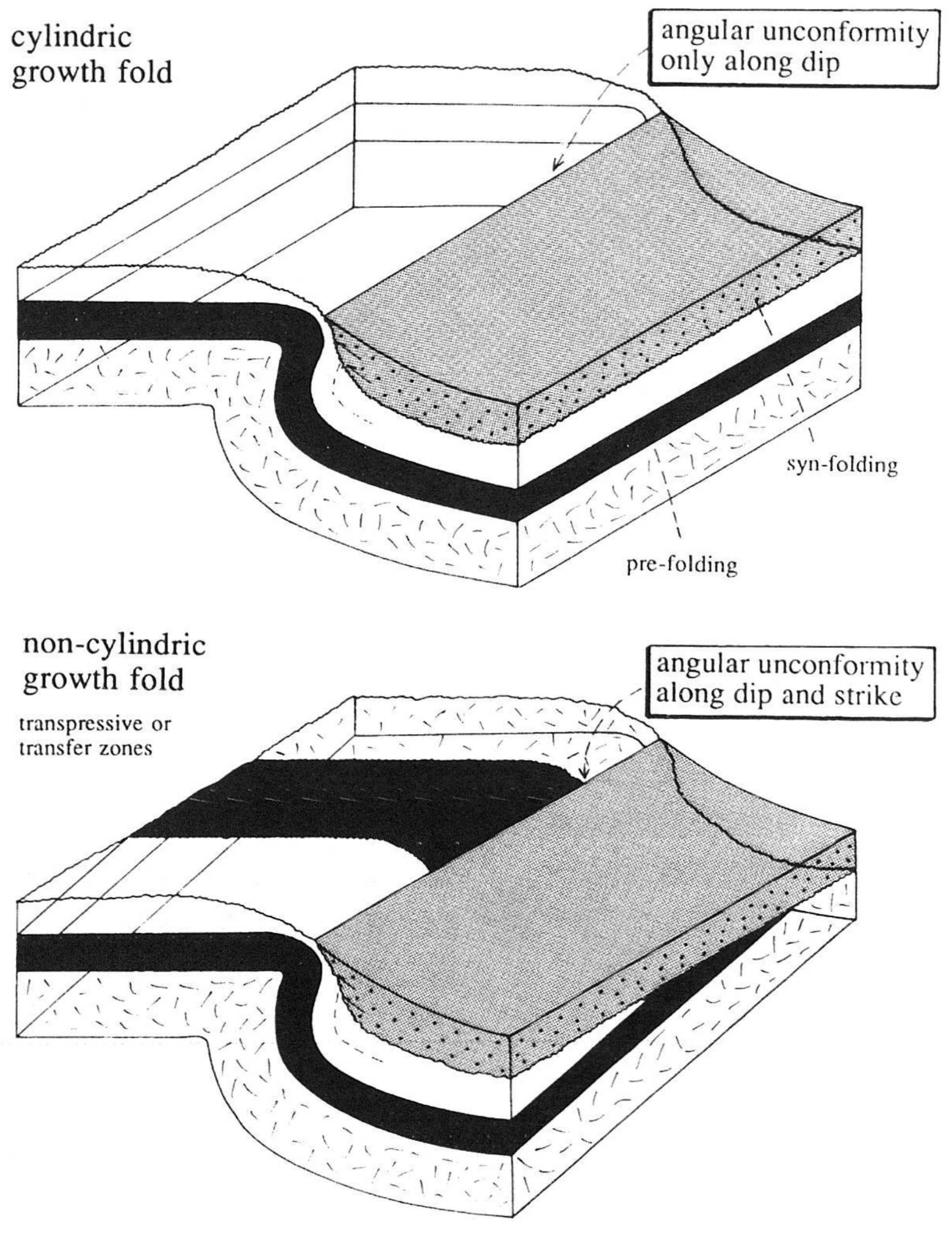

Fig. 17. The thrust belt front is characterized by clastic syntectonic deposition. During growth of the belt, clastic sediments onlap the southern margin of the frontal anticline. If the anticline is cylindric, an angular unconformity will form only along dip. Along structural undulations of the fold axis, due to buried anisotropies, the unconformity will develop both along dip and strike.

basement is overriding the sedimentary cover of the Venetian Alps and the thrust appears to be active also in recent time (Slejko et al. 1987), in spite of its internal position within the thrust belt.

Fault-propagation folding and fault-bend folding may coexist in one structure both in section and along strike. For instance, as proposed by Suppe & Medwedeff (1990), the breakthrough of a fault-propagation folding may occur in the lower limb of the footwall syncline, generating a ramp-flat trajectory. As a consequence, fault-bend folding overlaps fault-propagation folding in the same structure. This seems to be the case for the frontal anticline of the Venetian Prealps. Moreover it is possible to observe along strike the transition between the two main mechanisms of folding, separated by a transfer zone (the sinistral transpression and the coeval dextral transfer between the Bassano and the Maniago thrusts, at the transition between the Friuli Platform and the Belluno Basin, inset of Fig. 11). Triangle structures and drag folding may complicate the resulting geometry.

The front of the Venetian Prealps is characterized by a growth fold with onlap geometries of the molasse in the forelimb (Massari et al. 1986). The extension of the unconformities within the molasse is a function of the thrust belt structure and reflects areas of stronger uplift. Sequence boundaries in the southern fold limb are marked by angular unconformities with decreasing angles toward the foredeep suggesting the coeval activity of the frontal fold (Monte Grappa – Visentin Anticline). The unconformities are angular only along dip where the frontal fold presents a "cylindric" trend. Where there are structural undulations in the fold axis the unconformities are marked by angular relationships along both dip and strike. In summary, structures control the nature of the unconformities. A growth fold, with constant horizontal axis, generated by pure compression produces angular unconformities only along dip, while a growth fold generated by transpression produces angular unconformities both along dip and strike (Fig. 17). Therefore deep structures may influence the depositional geometries of clastic sediments.

Concluding remarks

Thrust belts are the result of compression or transpression deforming a crust that often has previously been stretched and thinned by tensional or transtensional tectonics. The inversion may be activated with a 180° range of angles with respect to the inherited tensional features, producing a variety of interference figures controlled by the orientation of the stress with respect to the peculiar thickness, faults and facies of the passive continental margin. The eastern Southern Alps presented here as an example, exhibit oblique inversion (20°–40°) with respect to the Alpine compression, and a greater angle (50°–70°) with respect to the Dinaric compression. The N 10° W–N 10° E trend of normal faults and N 70°–90° E trend of transfer faults controlling the tectonic evolution of the Mesozoic stretching has been partly inverted by the Dinaric compression oriented N 50°–80° E during Paleogene-Early Neogene times and by the Alpine maximum stress oriented N 20°–30° W during Late Paleogene-Neogene times. As a result, platform facies of the Trento Platform may partly be thrust southeastward over the basinal sequences of the Belluno Basin during southalpine compression. In general, any kind of Mesozoic N–S trending weakness zone (i.e. fault, thickness and facies variation) has been inherited and partly inverted by transpression during Alpine deformation. Undulations in the folds and thrusts occur above deep inherited structures and are then useful indicators of buried pre-existing heterogeneities. N–S trending, E-dipping normal faults have in general been passively cut by the Alpine compression, or reactivated as dextral transfer zones, while the W-dipping conjugate sets have been stronger inverted by sinistral transpression (e.g. the Giudicarie Belt emplaced at the margin between the Trento Platform and the Lombard Basin). The undulations in the frontal growth fold are also recorded by the unconformities in the molasse. Unconformities are angular only along dip where the frontal fold has a cylindric shape. Where there are structural undulations in the fold axis, the unconformities are marked by angular relationships both along dip and strike.

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