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THRUST TECTONICS EXAMPLES FROM THE VENETIAN ALPS(**)

CONTENTS

ABSTRACT

The Venetian Alps are part of the fold and thrust belt of the Southern Alps. The chain is SSE-vergent with a sigma 1 N20°-30°W oriented, and mainly formed during Neogene time. The paper illustrates a few examples of the belt and underlines the influence of the inherited Mesozoic features in controlling the structural evolution of the thrust belt. Fault-bend folding and fault-propagation folding are typical deformation mechanisms in the Venetian Alps. The front of the chain is marked by a triangle structure which migrated through time toward the foreland.

RIASSUNTO

Le Alpi Venete fanno parte della catena di sovrascorrimenti delle Alpi Meridionali. La catena veneta è SSE-vergente, con un sigma 1 orientato N20°-30°O, e si è sviluppata particolarmente durante il Neogene. Vengono presentati alcuni esempi significativi dei sovrascorrimenti della regione e sottolineata l'importanza dell'articolata eredità Mesozoica nel controllo della tettonica Alpina. Piegamenti per piani di sovrascorrimento ondulati e per propagazione dei piani di faglia sono meccanismi di deformazione tipici nelle Alpi Venete, caratterizzate da una struttura a triangolo frontale che ha migrato in sequenza verso l'anvanpaese durante l'evoluzione della catena.

KEY WORDS: Thrust tectonics, Mesozoic extension, Venetian Alps.

PAROLE CHIAVE: Tettonica di sovrascorrimenti, Estensione Mesozoica, Alpi Venete.

INTRODUCTION

This paper describes significative tectonic features of the Venetian Alps (Figs. 1, 2), a part of the Southern Alps, south of the Insubric Lineament. The Venetian Alps are a SSE-vergent thrust belt of mainly Neogene age (LEONARDI, 1965; CASTELLARIN, 1979; LAUBSCHER, 1983 e 1985; MASSARI *et al.*, 1986; ROEDER, 1989; DOGLIONI, 1987 e 1990).

The area has been investigated since the 19th century (i.e. MOJSISOVICS, 1879; TARAMELLI, 1882) and it has been the object of important stratigraphic and structural analysis (i.e. DAL PIAZ, 1907, 1912; TRENER, 1909; BOYER, 1914; CASTIGLIONI, 1939; CASTIGLIONI *et al.*, 1941; VENZO, 1940, 1977; TREVISAN, 1941; FERASIN, 1958; SEMENZA, 1960; BRAGA *et al.*, 1971; BOSELLINI, 1965, 1973; GNACCOLINI, 1967, 1968; CASATI & TOMAI, 1969; COUSIN, 1980; BOSELLINI *et al.*, 1981; CASTELLARIN, 1981; CASON *et al.*, 1981; MASSARI *et al.*, 1986, and references therein). These researches produced a fundamental improvement in the stratigraphic knowledge of the region, providing an indispensable base for tectonic studies. Since last century debates of this time were concerned whether the region was made up of folds or folds and thrusts. Actually, particularly in its southern border (Bassano - Vittorio Veneto) few thrusts outcrop and the arguments of those authors rejecting faults were understandable especially where what we now call triangle zones may exist. At that time only BUXTORF (1916) attempted to predict deep thrust interpretations on the basis of the volume balance, as adopted in the Jura Mountains.

In the Venetian Alps, at the time of the beginning of the application of the concept of balanced cross-sections (BALLY *et al.*, 1966; DAHLSTROM, 1969), the Italian National Oil Company (AGIP) established the presence of wide south-vergent thrusts in the area (Belluno Line) discovered during unsuccessful oil research (MARTINIS, 1966). At that time, the concept of the gravitational origin of the orogenic chains was alive because plate tectonics was still widely considered as no more than a possible theory. More recently the problem of the gravitational or "tangential" origin of the deformation of the Southern Alps has been addressed (DE SITTER & DE SITTER KOOMANS, 1949; SIGNORINI, 1954; LEONARDI, 1965; VAN BEMMELEN, 1966; DE JONG, 1967; SEMENZA, 1974; CASTELLARIN, 1979). Application of balanced cross-section methodology in the Southern Alps was produced by LAUBSCHER (1985), ROEDER (1985) and DOGLIONI & CASTELLARIN (1985).

GEOMETRY OF THE THRUST BELT

The geometry of the thrust belt is that of an imbricate fan (Fig. 3) with a conservative shortening of 30 km. The main thrusts are in order from the internal parts to the foreland, the Valsugana Line (Figs. 4, 5), the Belluno Line (Figs. 6, 7), the Moline Line (Fig. 2), the Tezze Line (Figs. 8, 9), and the Bassano Line (Fig. 13). The kinematic evolution of the thrust belt shows a general foreland in sequence progression. The crystalline basement largely outcrops in the hangingwall of the Valsugana thrust (Fig. 4) and is composed of Variscan metamorphosed green-schist facies rocks (phyllites, paragneisses, etc., D'AMICO, 1962) intruded by Late Carboniferous granitic bodies. Basement depth in the

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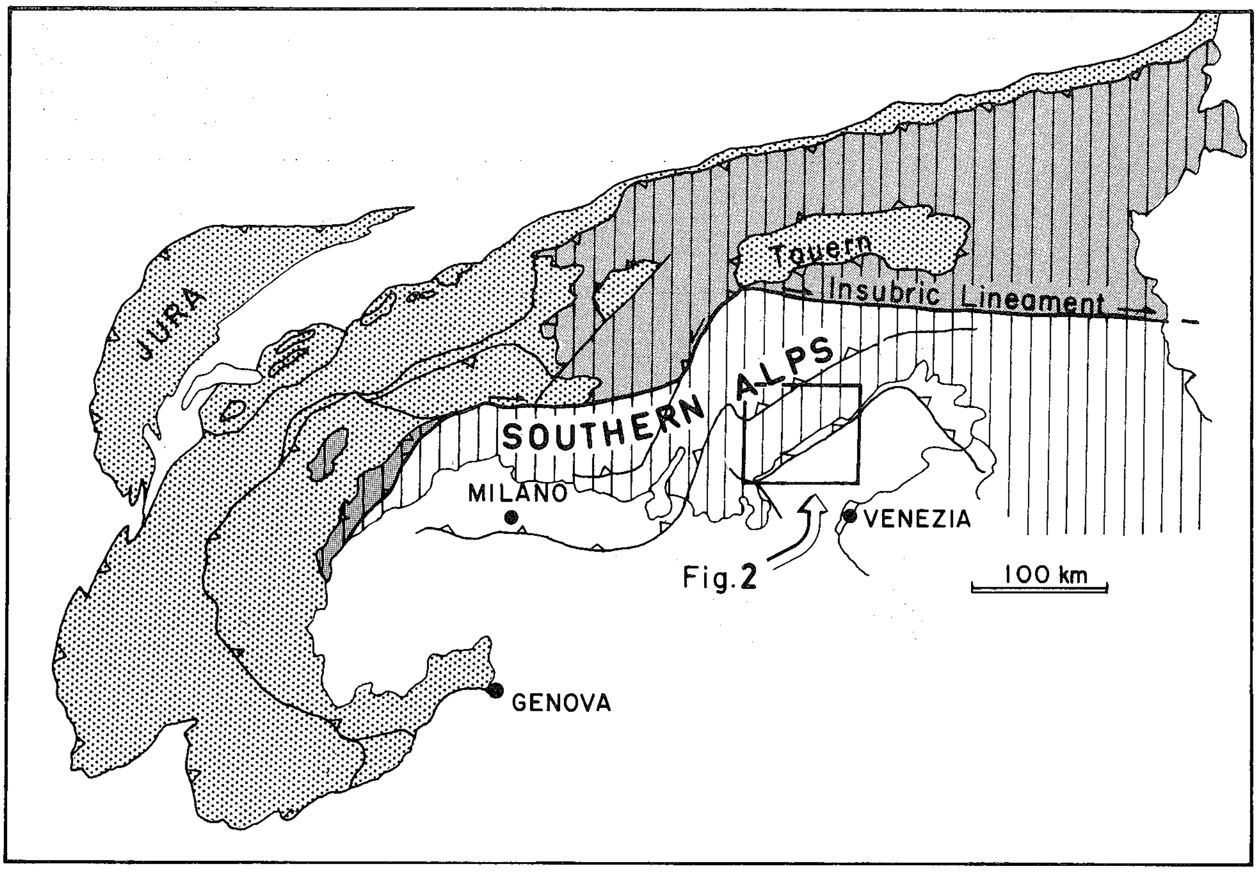


Fig. 1 - Location of the study area in the alpine context.

Venetian Plain is inferred by magnetic data (Cassano *et al.*, 1986) and by the assumption of the general hinterland dipping monocline typical of thrust belts. This is consistent with the southward rising of the basement discovered in the Assunta Well at 4747 m where Late Triassic dolomites onlap a Late Ordovician granite (Pieri & Groppi, 1981). Triangle zones are present along the Valsugana thrust where the basement is sometimes wedged within the sedimentary cover, or it produces a triangle in the Valsugana Valley where the Valsugana thrust faces a north-vergent basement involving backthrust to the north of the Asiago Plateau. Major undulations along the Valsugana thrust occur again in correspondance of inherited features, i.e. the sinistral N0°-10°E striking transpressive undulation of Borgo Valsugana which occurs in corrensppondance of an inherited structural high as supported by the reduced thickness of the sedimentary cover. The Valsugana thrust is characterized in its western segment by wide outcrops of the crystalline Variscan basement which is often cut by several minor thrust planes subparallel to the main Valsugana thrust. The thrust is generally in ramp (Fig. 5) and abandoning earlier staircase trajectories in the sedimentary cover probably due to the poor possibility to fold by flexural slip.

Within the sedimentary cover the thrusts are characterized by cut-off angles ranging between 5° and 45°. Preferential decollement layers are the Tertiary Possagno Marls, the Late Cretaceous Scaglia Rossa, and other, buried levels within the Late Permian and Triassic sequences. The thrust planes assume steeper angles when a footwall syncline is present. Footwall synclines are well developed in Cretaceous pelagic thin bedded rocks (Biancone and Scaglia Rossa) whose folding is accomodated by intense flexural slip. Chevron folds are particularly common in these two formations and their amplitude and wavelength decrease away from the thrust planes.

The frontal part of the thrust belt is characterized by a triangle zone (Figs. 2, 3) which generates a southward dipping monocline typical of the Venetian foothills between Bassano and Vittorio Veneto. The frontal triangle zone is the most peculiar structure of the foreland and its presence is indicated by: 1) the general absence of an important thrust at the base of the mountains (Monte Grappa - Visentin Anticline); 2) the necessity of a thrust at the base of the anticline to resolve the volume problem of the structural high; 3) the south-dipping monocline in the frontal part of the chain which is typical for the triangle zones (i.e. Bally *et al.*, 1966; Jones, 1982; Boyer & Elliott, 1982; Vann *et al.*, 1986) which cannot be explained as a footwall syncline; 4) the presence of north-vergent backthrusts (i.e. in the Possagno and Follina areas, Braga, 1970; Zanferrari *et al.*, 1982). The interpretation presented in Fig. 3 of the triangle zone is only one among other possibilities: i.e. there are not clear indications of the southward continuity of the decollement necessary to adsorbe the amount of displacement. This could be in turn expressed through pressure solution cleavage or more probably in antiformal stack duplexes within the antlicline core of the triangle zone.

The triangle zone between Bassano (Schio?) and Vittorio Veneto seems to be connected with a ramp-flat geometry of the deep seated blind undulate thrust which generated a growth fold (The Monte Grappa -

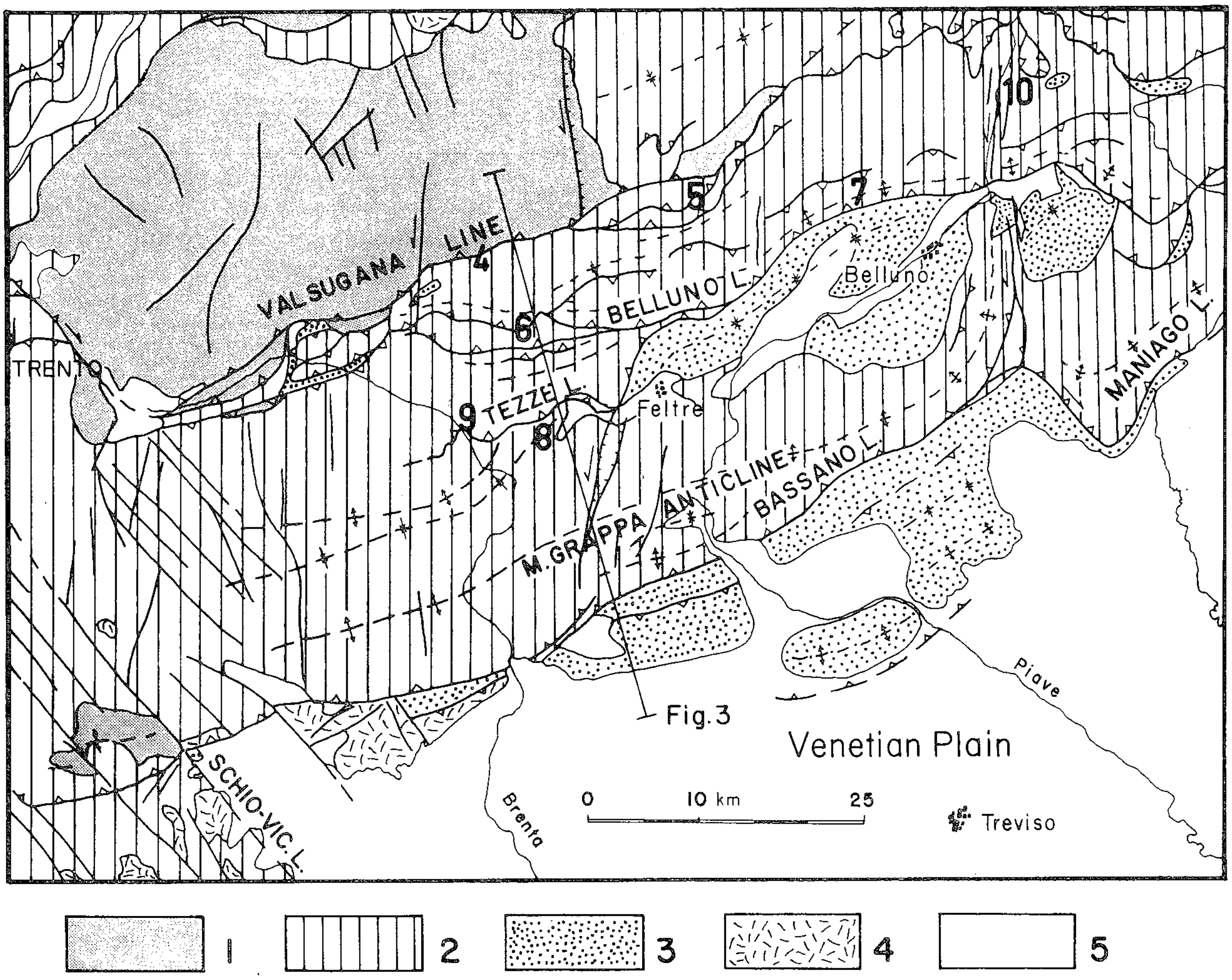


Fig. 2 - Simplified tectonic map of the Venetian Alps. Legend: 1, Hercynian crystalline basement and Permian Ignimbrites; 2, Late Permian and Mesozoic sedimentary cover; 3, Tertiary sediments, i.e. flysch and molasse; 4, Triassic and Tertiary volcanics; 5, Quaternary. Numbers indicate the relative figures shown in the text.

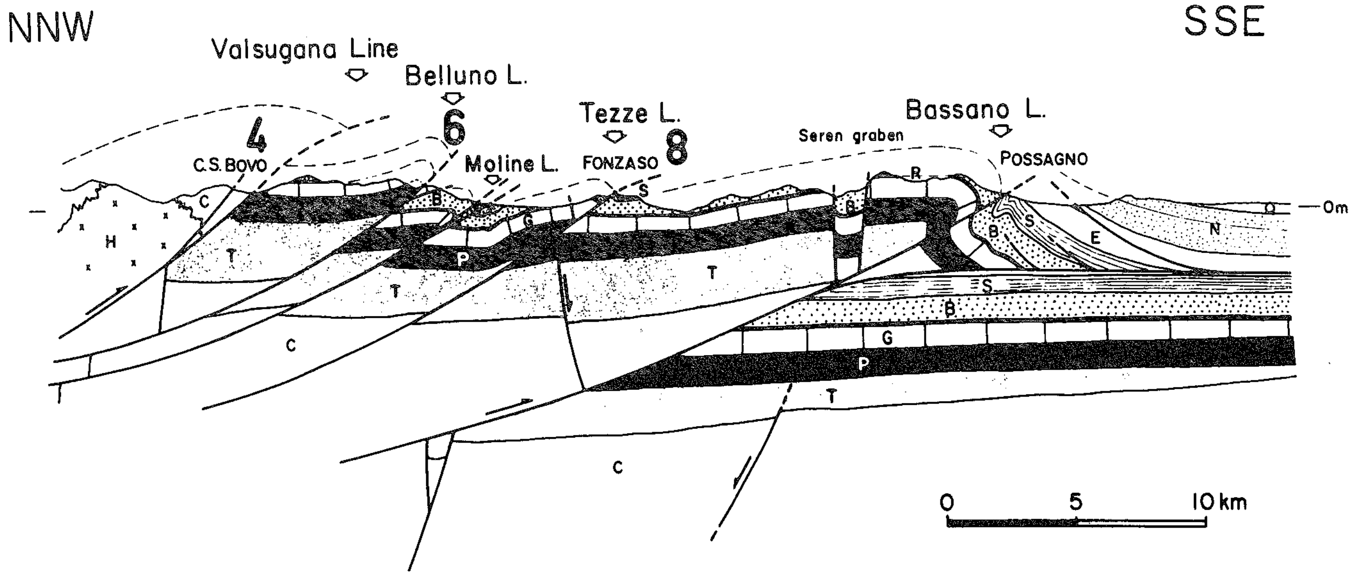


Fig. 3 - Balanced cross-section of the Venetian Alps (after Doglioni, 1990). See Fig. 2 for location. Legend: C, crystalline basement; H, Late Hercynian granite; T, Late Permian-Lower and Middle Triassic formations; P, Late Triassic (Dolomia Principale); G, Liassic platform facies (Calcari Grigi) gradually southward passing to Liassic-Dogger basinal facies in the Venetian Plain (Soverzene Formation, Igne Formation, Vajont Limestone); R, Dogger-Malm basinal facies (Lower and Upper Rosso Ammonitico, Fonzaso Formation; B, Early Cretaceous (Biancone); S, Late Cretaceous (Scaglia Rossa); E, Paleogene (Possagno Marls, etc.); N, Late Oligocene-Neogene Molasse; Q, Quaternary. Numbers above the thrusts indicate the relative figures shown in the text.

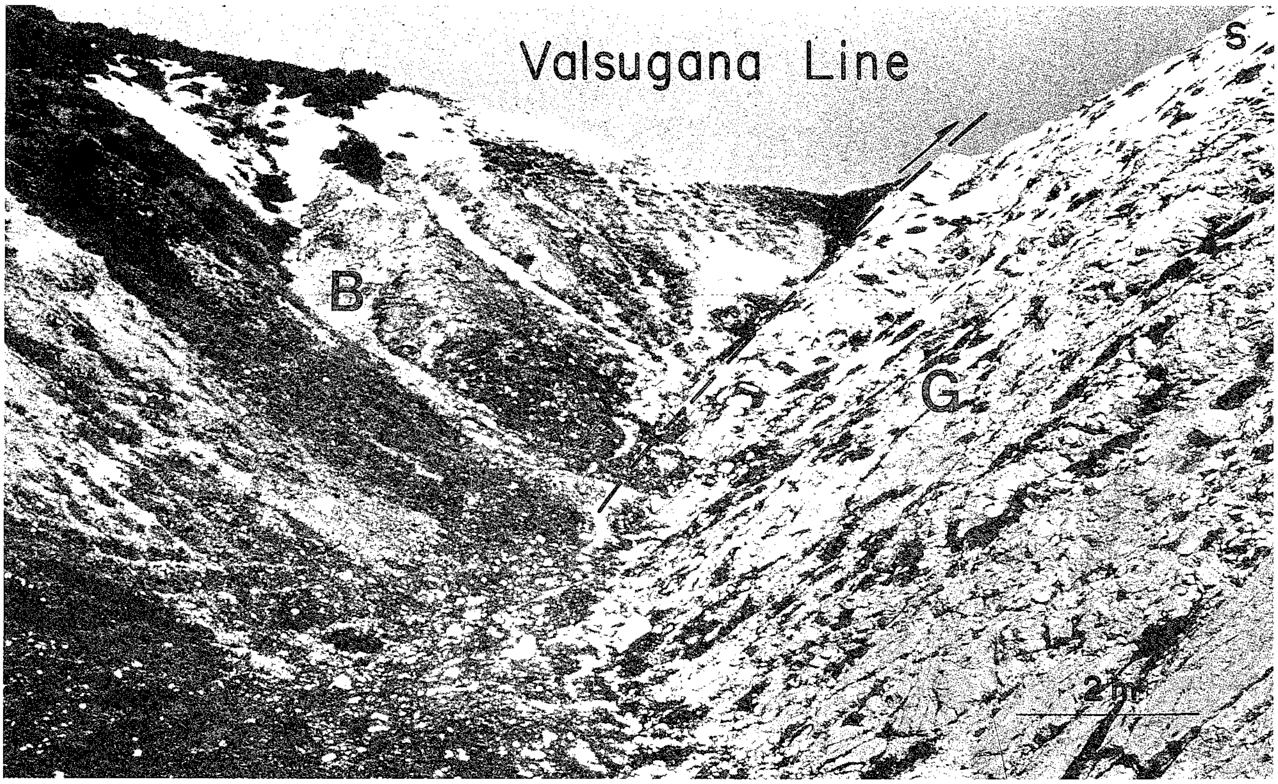


Fig. 4 - The Valsugana thrust to the north of Passo Broccon. B, Hercynian granite (basement); G, Calcari Grigi, Liassic. This outcrop is located a few km westward of the cross-section of Fig. 3. See Fig. 2 for location.

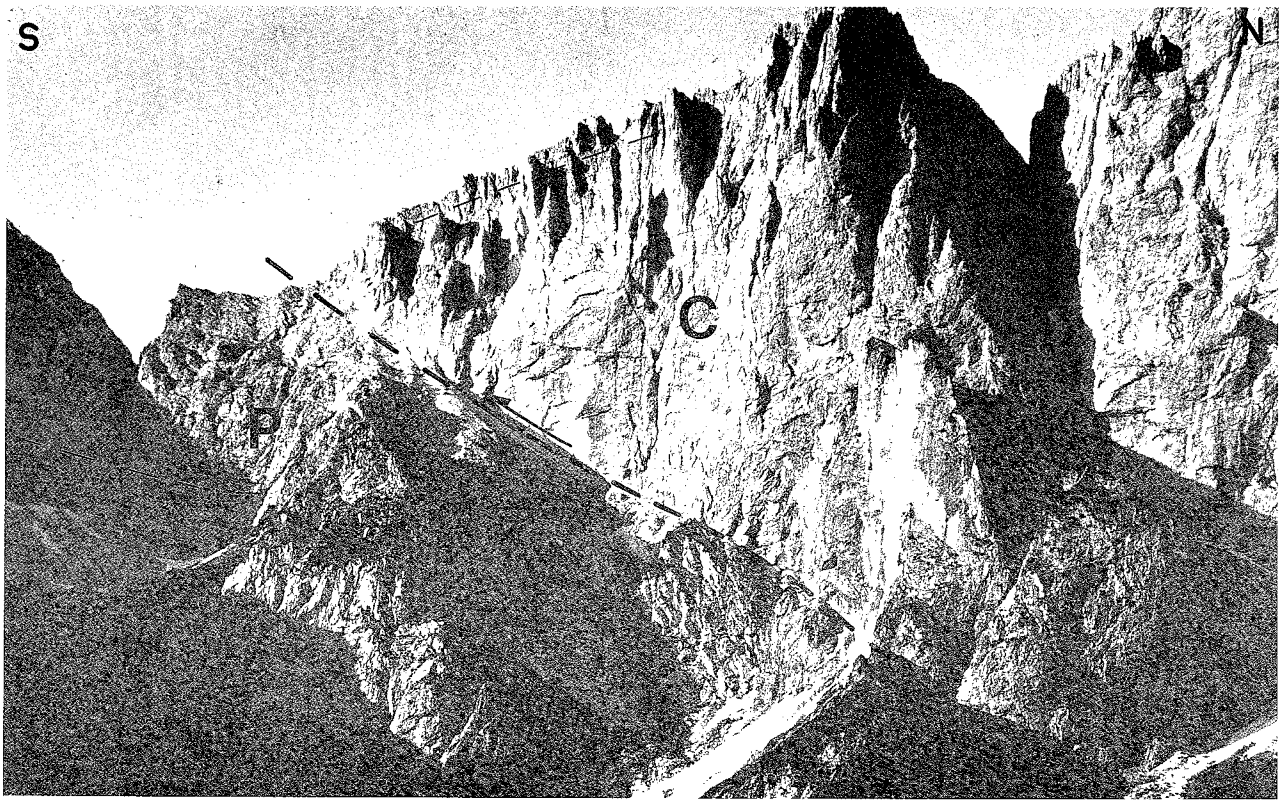


Fig. 5 - The Valsugana thrust in the eastern cliff of the Piz de Sagron, in the northern part of the Vette Feltrine. Sciliar Dolomite (Ladinian) in the hangingwall and Dolomia Principale (Norian) in the footwall. See Fig. 2 for location.

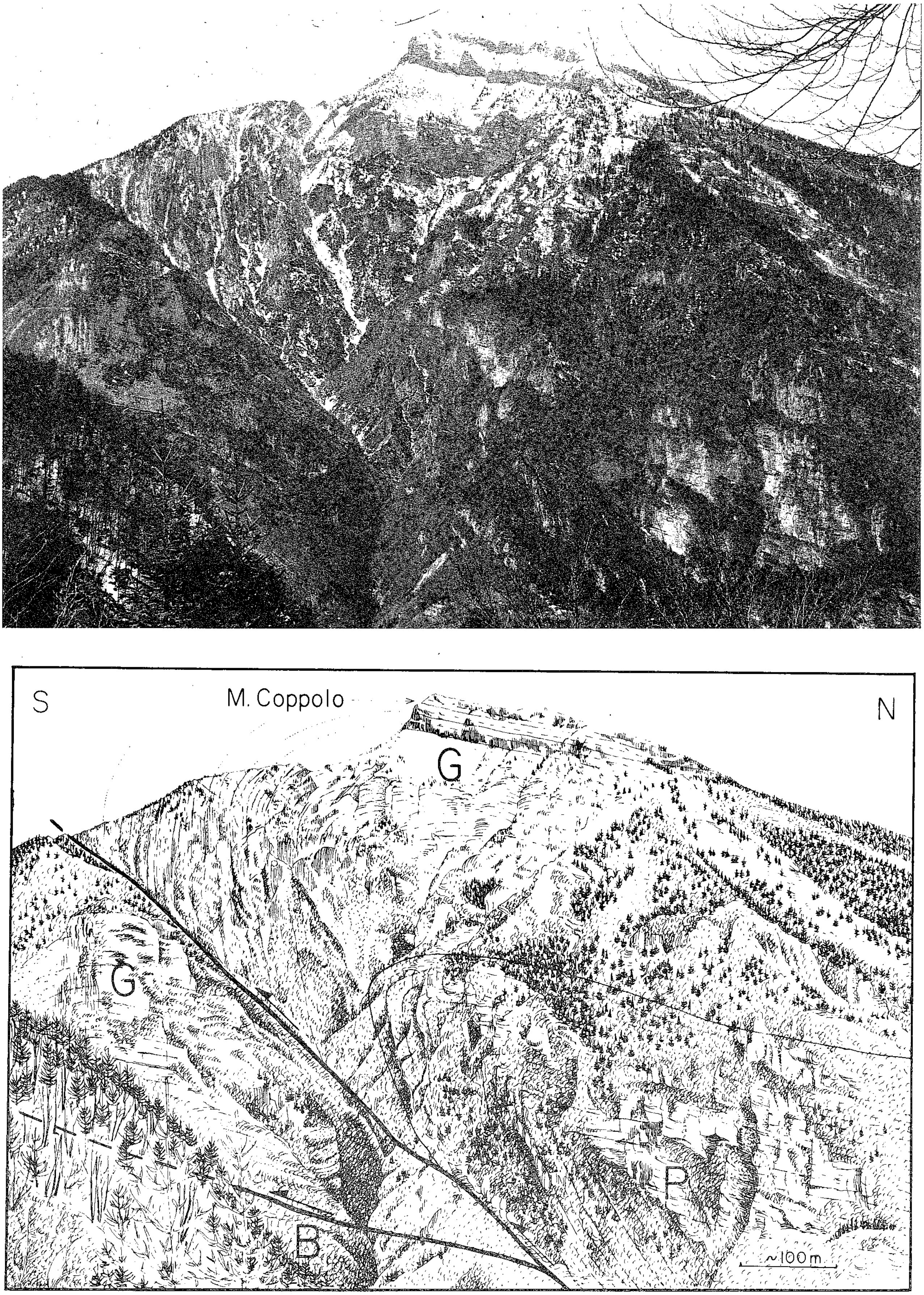


Fig. 6 - The Belluno thrust with a minor display as it outcrops along the section of Fig. 3, in the Cismon Valley. The vertical or reverse forelimb of the hangingwall anticline indicates a fault-propagation folding. Legend: P, Dolomia Principale (Norian) and Rhaetian limestone; G, Calcari Grigi, Liassic; B, Biancone, Early Cretaceous. See Fig. 2 for location.

Fig. 7 - The fault-propagation anticline in the Belluno thrust hangingwall near Peron (10 km NW of Belluno). Comparing Fig. 6, we note that the length of the forelimb is eastward increasing, suggesting a relative increment of the Belluno thrust displacement. See Fig. 2 for location.

Visentin Anticline). This was active at least during Late Miocene times because Tortonian and Messinian sediments onlap with a gradually smaller inclination the southern limb of the anticline (MASSARI *et al.*, 1986). Sequence boundaries in the southern fold limb are marked by angular unconformities with an angle that is decreasing toward the foredeep suggesting the coeval activity of the frontal fold (Monte Grappa - Visentin Anticline). To the north, the Belluno Line may have been a blind thrust generating a triangle zone during earlier stages of the deformation, later rising at the surface in the northern limb of the Belluno Syncline. This is supported by the steep attitude of the northern limb of the Belluno Syncline which is difficult to explain geometrically as a simple footwall syncline. We also note that triangle zones mainly occur in the Mesozoic Belluno Basin, rather than in the neighboring platforms. In fact the Belluno Syncline is developed in the deepest structural zone with thick basinal lithofacies. This earlier structural situation had an important influence in the morphology and source areas of the hydrographic pattern during the Late Miocene.

MESOZOIC TECTONICS

The study area was part of a Mesozoic continental margin, according to stratigraphic analysis, i.e. facies and thickness changes (ABOUIN, 1963; BOSELLINI, 1973; WINTERER & BOSELLINI, 1981). The area can be divided into three main structural sectors during Mesozoic time. These are from west to east: the Trento Platform, the Belluno Basin and the Friuli Platform. The Mesozoic normal faults trend mainly N10°W-N10°E. We can argue that the Trento Platform, the Belluno Basin and the Friuli Platform were bounded by crustal normal faults, mainly N-S trending, acting at different times and with different displacements during Jurassic time and during at least the Early Cretaceous. The eastern border of the Trento Platform is also marked by several N-S trending 50-200 m wide, and 100-200 m high sedimentary dykes in the Biancone sediments observable around the Arsiè Lake. Those dykes could represent the superficial tensional deformation of deep seated active (Early Cretaceous) listric normal faults. Early Cretaceous (syn-Biancone Formation) normal faults outcrop along the Cismon Valley (i.e. Val Rosna section).

An example of synsedimentary normal fault is illustrated in Figs. 10, 11, 12. This Liassic growth fault is placed at the western border of the Friuli Platform, close to a Neogene sinistral transpressive fault (Col delle Tosatte Line) which probably used the highest and steepest part of a pre-existing large Mesozoic synsedimentary normal fault located parallel to the small one described here. This outcrop provides the possibility of seeing the structure in three dimensions: the listric shape in the perpendicular section and the bifurcation with oblique-lateral ramps in the frontal section. The meso and microstructures (i. e. striations) confirm

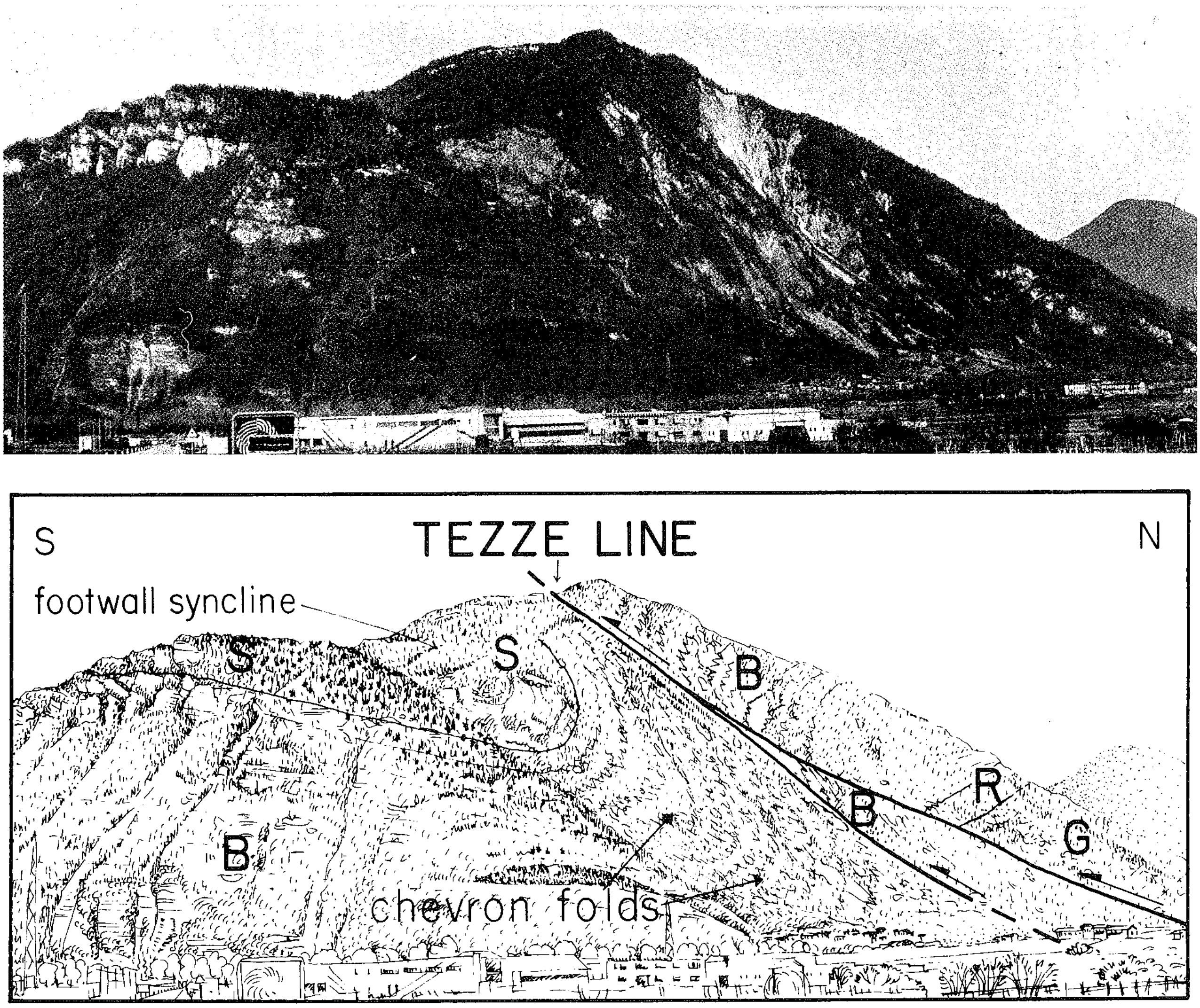


Fig. 8 - The Tezze thrust near Fonzaso. The footwall syncline would suggest a fault-propagation folding origin for the entire feature. Note the chevron folds near the thrust plane. Pressure solution is very consistent within the fold. Legend: G, Calcari Grigi, Liassic; R, Lower Rosso Ammonitico, Fonzaso Formation, Upper Rosso Ammonitico, Dogger and Malm; B, Biancone, Early Cretaceous; S, Scaglia Rossa, Late Cretaceous. See Figs. 2 and 3 for location.

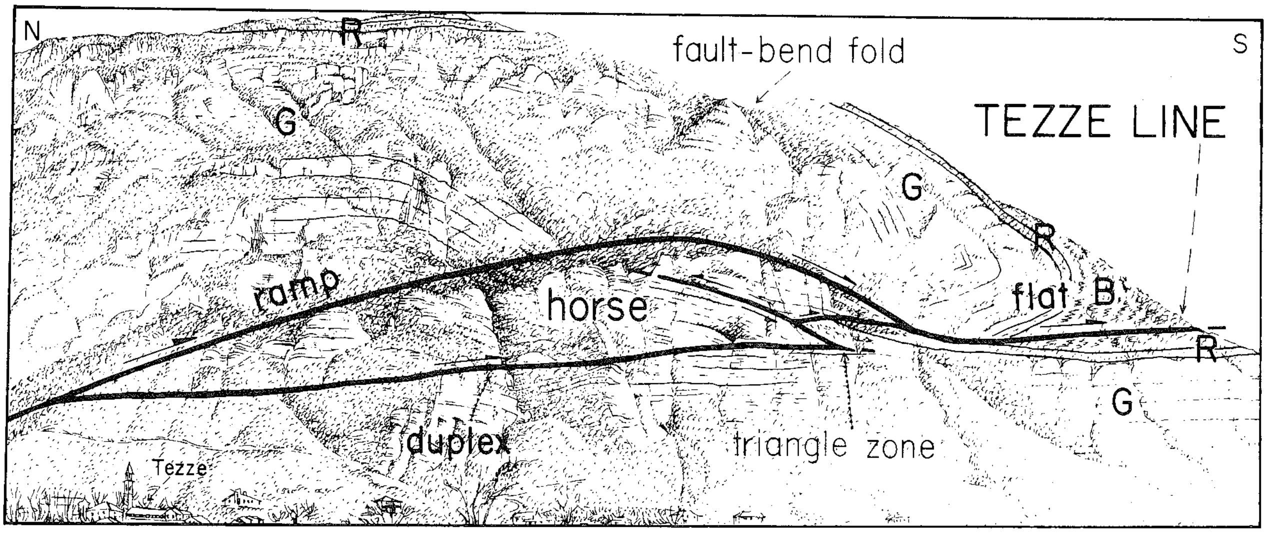
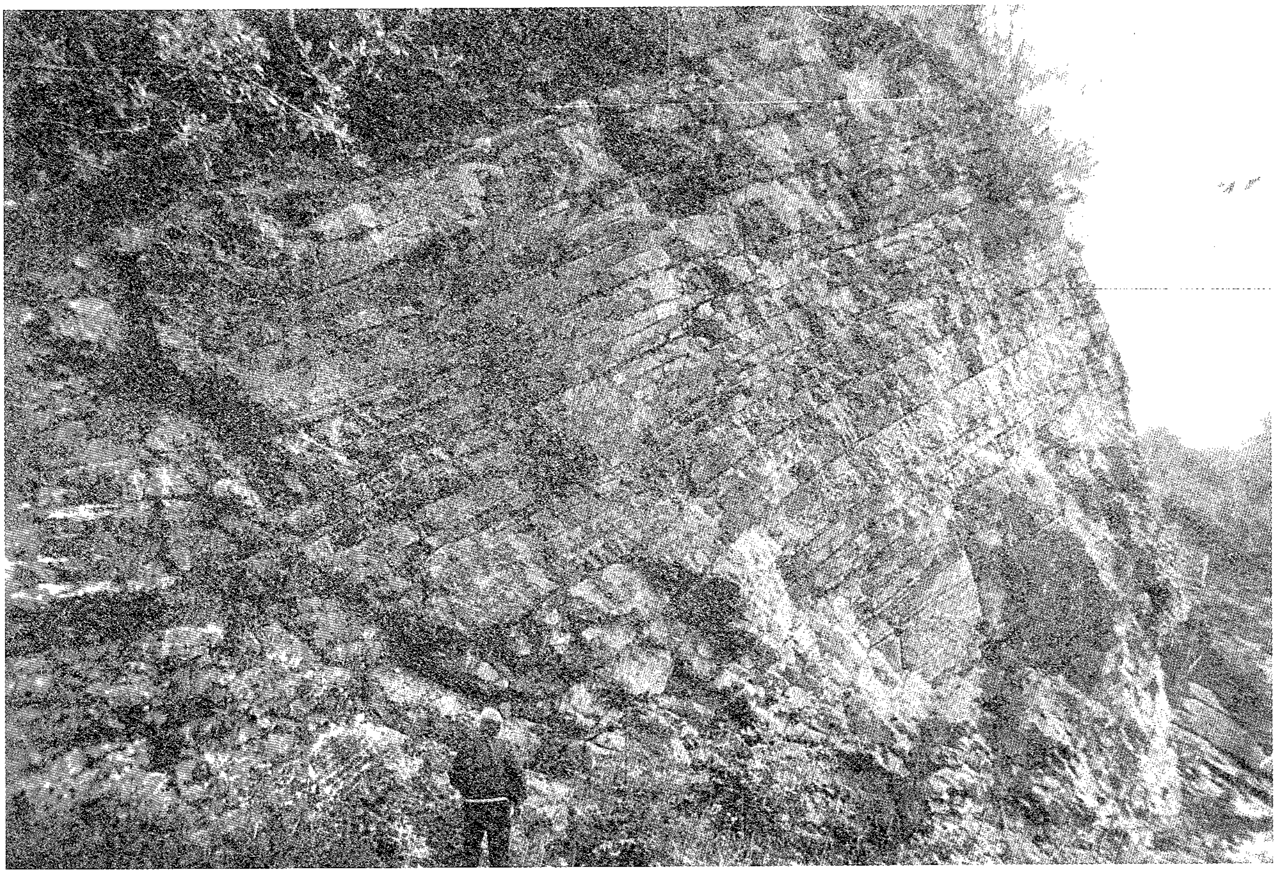


Fig. 9 - Hand drawing of the natural cross-section outcropping to the east of the Tezze Village (Valsugana). Legend: G, Calcari Grigi (Liassic); R, Ammonitico Rosso (Dogger-Malm); B, Biancone (Early Cretaceous). Note that the anticline is a combination of fault-bend folding and fault-propagation folding. This structure is located to the west of Fig. 8 and shows the lateral variation of the Tezze thrust, close to its tip line (Fig. 2).



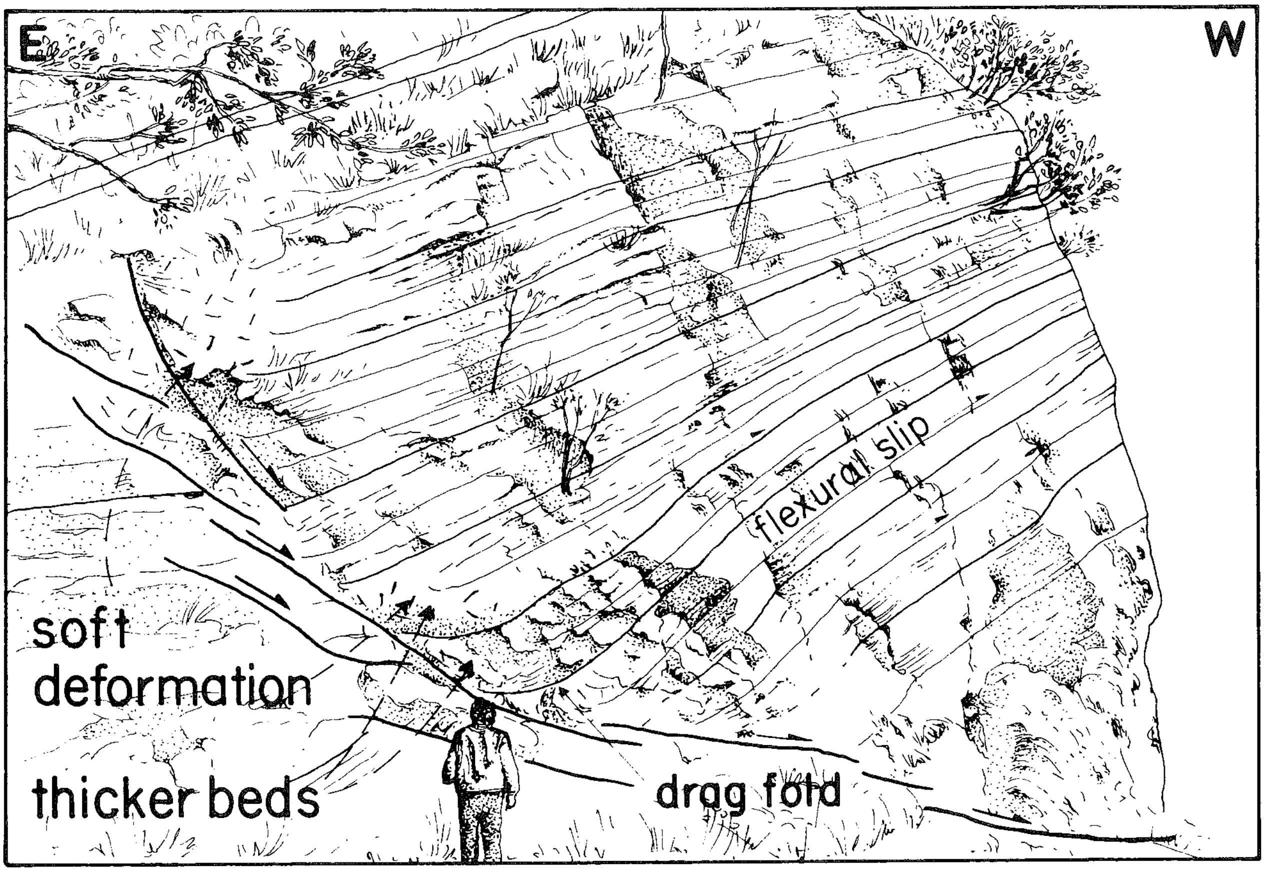


Fig. 10 - Perpendicular view of a Liassic synsedimentary growth fault in the Igne Formation. Vajont gorge, old Enel road. In this outcrop (this figure and the next one) it is possible to observe a rare case of listric normal fault in three dimensions. Note the en-échelon pattern of the small faults belonging to the shear zone, the soft deformation due to partly unconsolidated sediments and the thickening of the beds close to the fault. Note also in the upper left the bedding suturing the structure. See Fig. 2 for location.

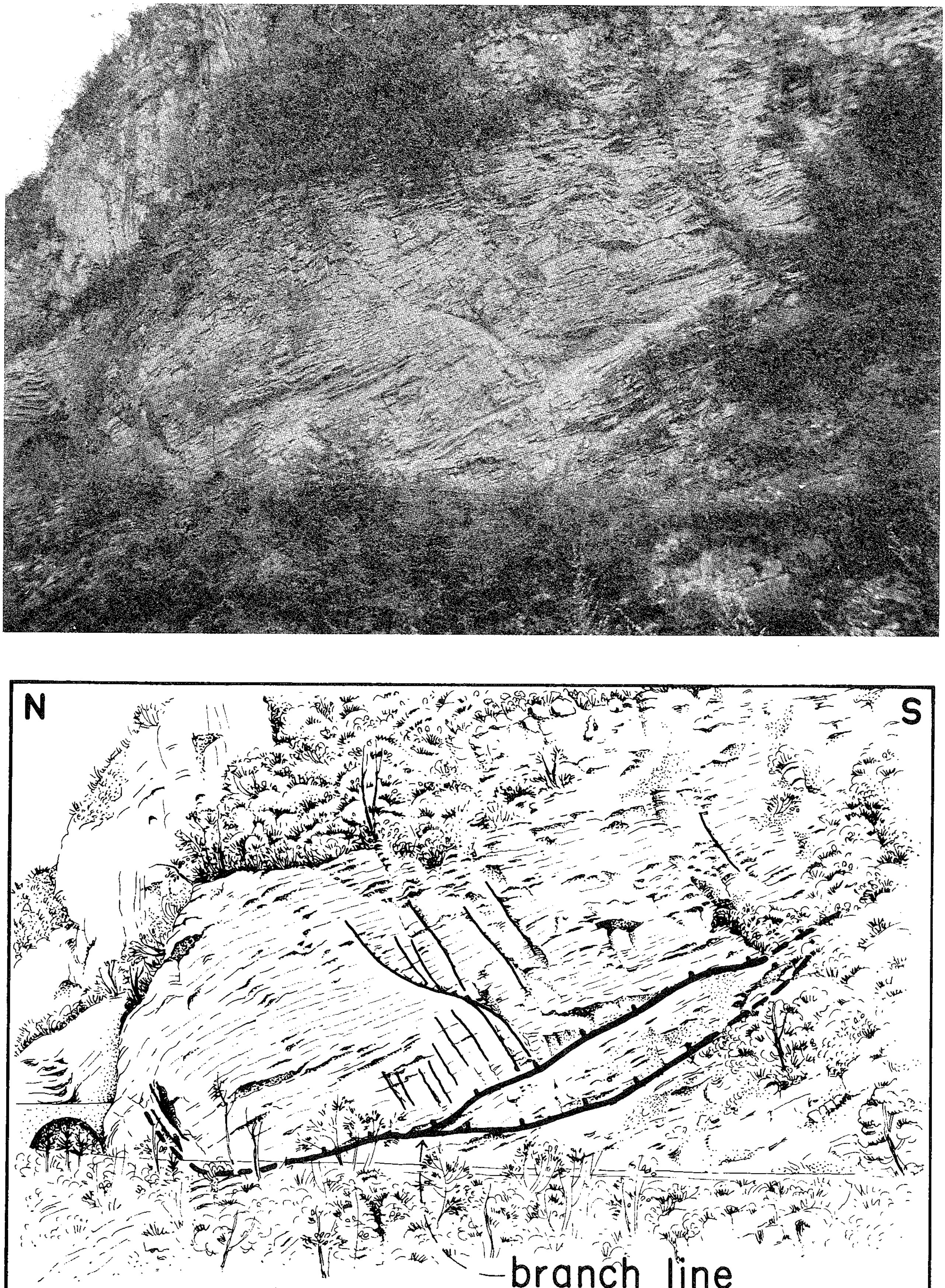


Fig. 11 - Frontal view of the Liassic growth fault in the basinal Igne Formation of Fig. 10, at the Vajont gorge. Note the branch line, the lateral and oblique ramp geometry of the listric fault plane. Normal striations confirm that the hangingwall of the normal fault moved toward the observer. Small conjugate fractures and faults are confined to the hangingwall.

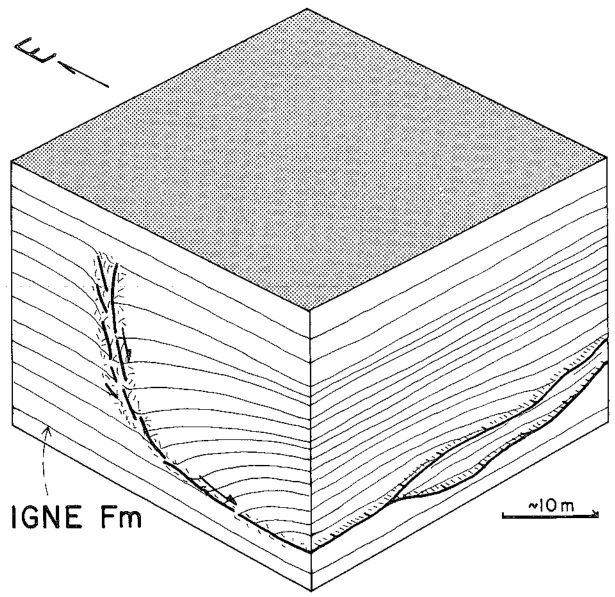


Fig. 12 - Schematic block-diagram of the Liassic growth fault. A regionally more important feature had to be the Col delle Tosatte Line, northern prolongation of the Fadalto Line, a likely Mesozoic normal fault at the western Friuli Platform margin, reactivated as a Neogene sinistral transpressive fault.

the N270° sense of shear. The syn- Igne Formation (Liassic basinal sediments) age is confirmed by: undeformed beds suturing the *en-échelon* pattern of normal faults; by the soft deformation close to the shear zone indicating the partly unconsolidated state of the basinal sediments, and by the thickening of the beds close to the growth fault. The thickening is of the order of 5-10 cm per bed which could indicate a similar subsidence rate along the fault in the range of 20,000 years if we assume that each couple (limestone-marls) represents a 5th order (high frequency) Milankovitch cycle.The basement and the sedimentary cover of the Venetian Alps were broken by N-S trending normal faults and N60-90°E transfer faults (the paleo-Valsugana Line ?, Fig. 3) during the Late Permian-Mesozoic rifting phases. These features have been cut, reused or deformed during the alpine inversion, interpreted as transpressive in the central and eastern Alps (Laubscher, 1983). The thrust belt is not cylindrical and the strain continuously changes along strike. In a map view of the area (Fig. 2), the thrusts show an anastomosing pattern along strike, maintaining a constant shortening which can conservatively be calculated as 30 km (Fig. 3). Local structural undulations in the general N60-80°E trend of the chain (fold axis, direction of thrust planes, etc.) everywhere occur in correspondance to inherited features in the basement and in the Mesozoic sedimentary cover which are arranged

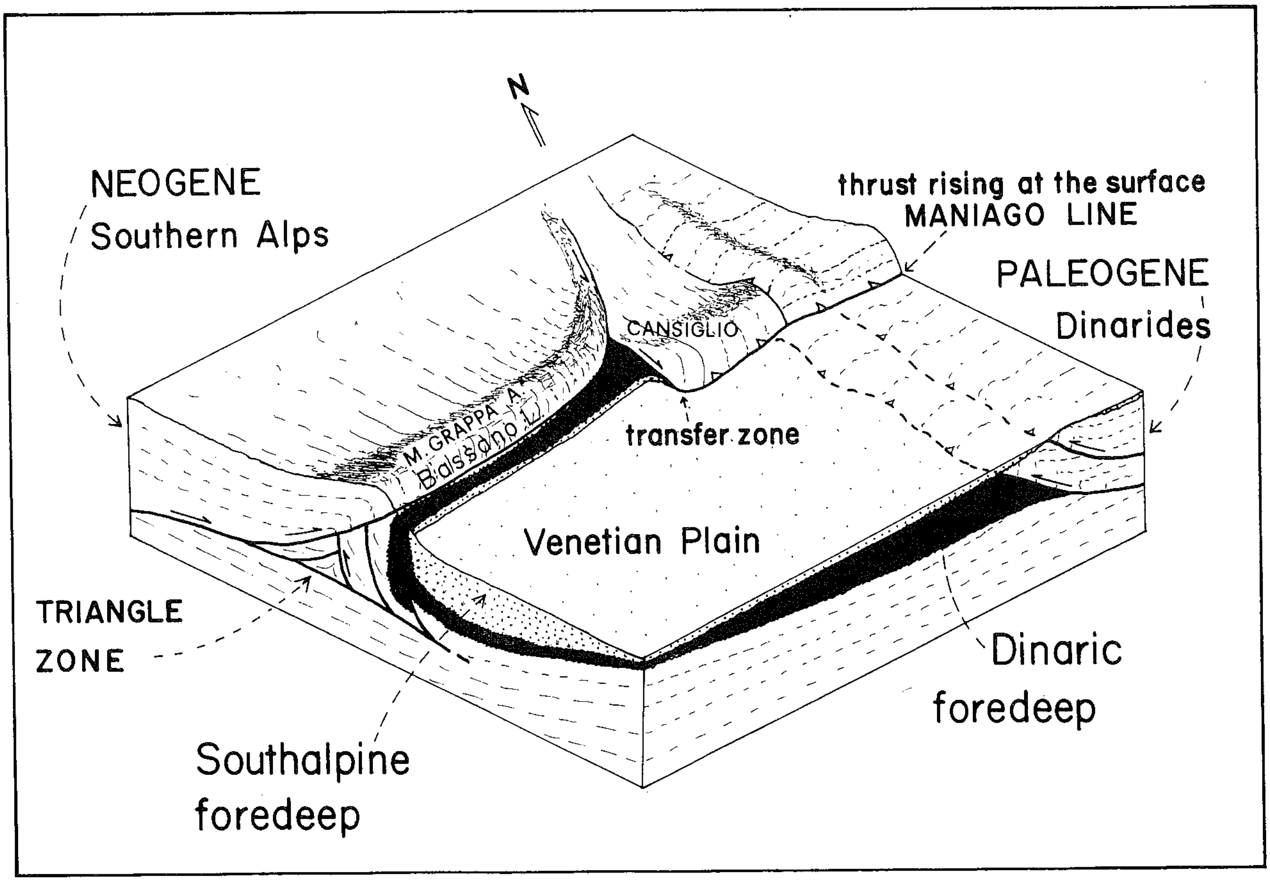


Fig. 13 - Schematic picture of the Venetian Alps front. The foothills are characterized by a triangle zone. The deep thrust plane (Bassano Line) reaches the surface (Maniago Line) through a transfer zone (Caneva Line). The Venetian Plain represents the foredeep of two opposite thrust belts. The geometry of the foreland basin changes from the triangle zone to the normal thrust to the east. In the first case the clastic sediments are pushed southwards, tilted and eroded. In the second case they are simply thrusted.

in almost N-S trending basins and swells. The present tectonic configuration is due to the inherited Mesozoic background. The structural evolution of the area followed boundary features as transfer zones at horst margins (i.e. at the Trento Platform and Friuli Platform margins) which have influenced the geomorphologic evolution of the area. The Asiago pop-up (BARBIERI, 1987) constitutes the western part of the study area, and is a wide plateau formed on the inherited Trento Platform (horst). On the basis of thickness and facies changes the amplitude of the Trento Platform was probably wider in the east during Jurassic times (Seren Valley) and probably retreated (as horst, with basinal facies) by about 10 km during Cretaceous times (eastern margin of the Asiago Plateau, Valsugana Valley). The Tezze Line develops at this final eastern margin of the Trento horst and undulates in oblique and lateral ramp (sinistral transpression) at the intersection with the inherited Seren Valley alignment.

Commonly the inherited tensional Mesozoic areas have been reactivated in transpressive zones and are transfer zones between two different styles of deformation. The Caneva Line and the Fadalto Line are two respectively dextral and sinistral transpressive zones at the eastern margin of the Belluno Basin. The Caneva Line represents the transfer zone of the frontal triangle zone eastward termination (Fig. 13). The Fadalto transpression was emplaced at the western termination of the Friuli Platform.

CONCLUSIONS

The Venetian part of the Southern Alps (N-Italy) is a Neogene south-vergent thrust belt with 30 km of conservative shortening. From north to south the main thrusts are in order the Valsugana Line, the Belluno Line, the Tezze Line and the Bassano and Maniago Lines. The thrusts trend N60°-80°E and they developed from an inherited N10°W-N10°E trending normal fault pattern of the Mesozoic continental margin. The tensional activity subdivided the region into three main provinces which are, from west to east, the Trento Platform, the Belluno Basin and the Friuli Platform. These earlier features strongly influenced the evolution of the thrust belt. In fact any kind of structural undulation along strike of the thrust belt is associated with preexisting Mesozoic faults, thickness and facies variations. The thrusts are arranged in an imbricate fan geometry and show a frontal triangle zone from west of Bassano to Vittorio Veneto. The triangle zone ends at the west and at the east at transfer faults (the Schio-Vicenza Line and the Caneva-Montaner Line). To the east of the Caneva-Montaner Line the external thrust rises at the surface (Maniago Line). The dextral Caneva-Montaner transfer fault is located at the Mesozoic Belluno Basin - Friuli Platform margin and probably reactivated the steepest part of a Mesozoic normal fault. To the north, the Belluno Line was probably a blind thrust during earlier stages of the deformation, later outcropping both in the northern and southern limbs of the Belluno footwall syncline.

In a map view of the area, the thrusts show an anastomosing pattern along strike, maintaining a constant shortening. From west to east, a wide box-fold (the Asiago pop-up) was emplaced on the Mesozoic Trento Platform. This feature becomes suddenly smaller when the deformation enters the Mesozoic Belluno Basin, loosing the basement backthrust. Going eastward, the ramp anticline progressively decreases its wavelength, probably due to a gradual variation in dip of the ramp of the Bassano Thrust. The anticline ends in a sinistral transpressive way at the Belluno Basin - Friuli Platform margin.

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