11. Tectonics of the Dolomites and the Venetian Alps

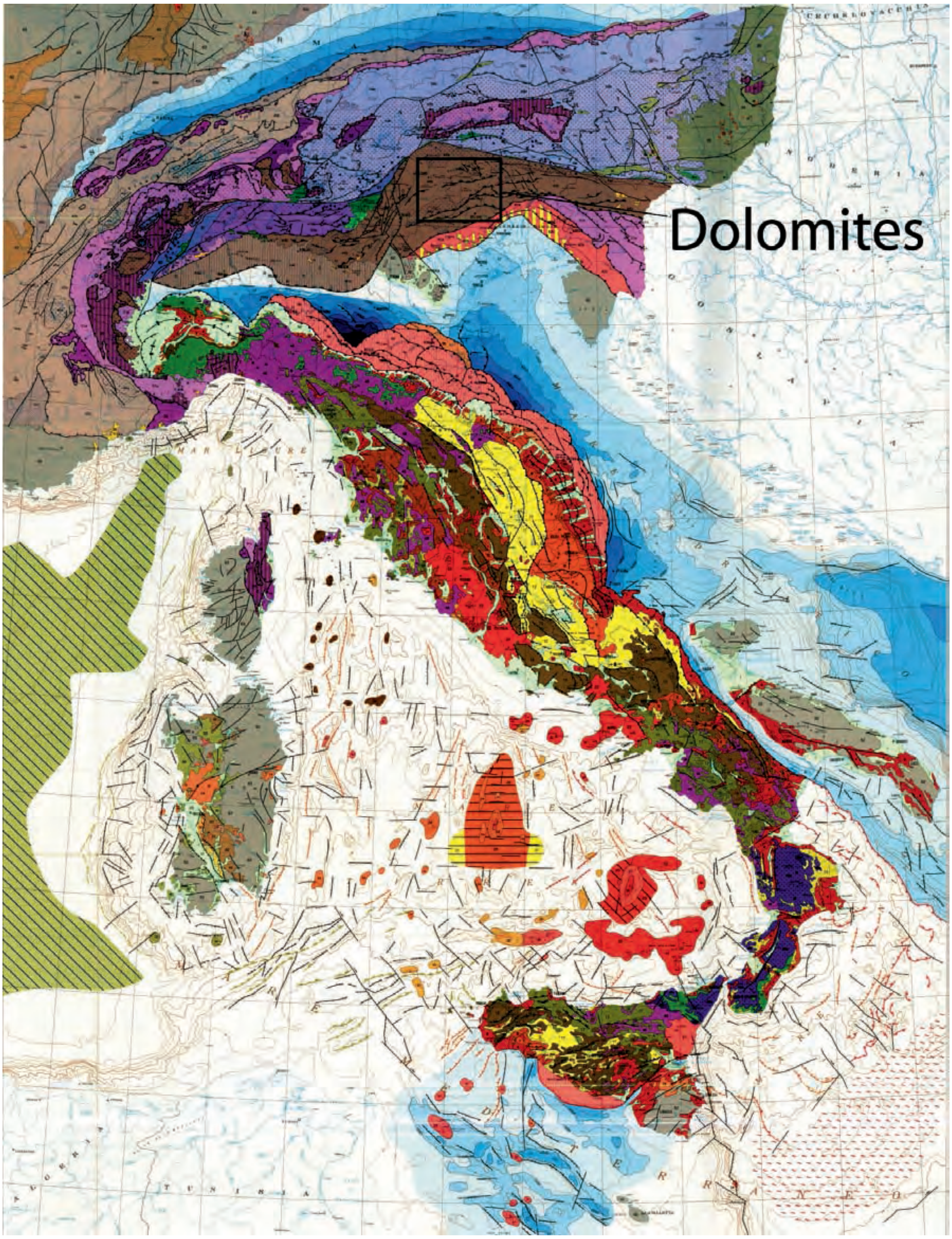


Fig. 225 - Structural Model of Italy (after BIGI *et alii*, 1989).

Fig. 226 - Structural model of the Alps and the Northern Apennines (Bigi *et alii*, 1989).

This chapter will describe the main structural grain of the Dolomites and the Venetian Alps, a part of the eastern Southern Alps, south of the Insubric Lineament (figs. 225 - 227; see olso the map at the end of the book). It is a SSE-vergent fold and thrust belt (figs. 228 - 231) of mainly Paleogene-Neogene age (DAL PIAZ 1912; LEONARDI 1965; CASTELLARIN 1979; LAUBSCHER 1985, MASSARI *et alii* 1986; DOGLIONI 1987; ROEDER 1989) probably produced by the dextral transpression in the central-eastern Alps (LAUBSCHER 1983). The chain deformed a pre-existing Mesozoic passive continental margin (BOSELLINI 1965; 1973; BERNOULLI *et alii* 1979; Winterer & BOSELLINI 1981).

The Venetian Alps have been shortened mainly during Neogene times (VENZO 1939; MASSARI *et alii* 1986; DOGLIONI 1987) and not deformed by the Dinaric chain of which constituted the unfolded foreland during Paleogene times (DOGLIONI & BOSELLINI, 1987).

The Dolomites to the north, in post-Variscan times, underwent a number of tectonic events, which may be summarized as follows: Permian and Triassic rifting phases broke the area into N-S trending basins with different degrees of subsidence. A Middle Triassic transtensive-transpressive event then deformed the region along a N70°-90° trend, generating flower structures within the basement . Volcano-tectonic domal uplift and subsequent caldera formation occurred at the same time as the

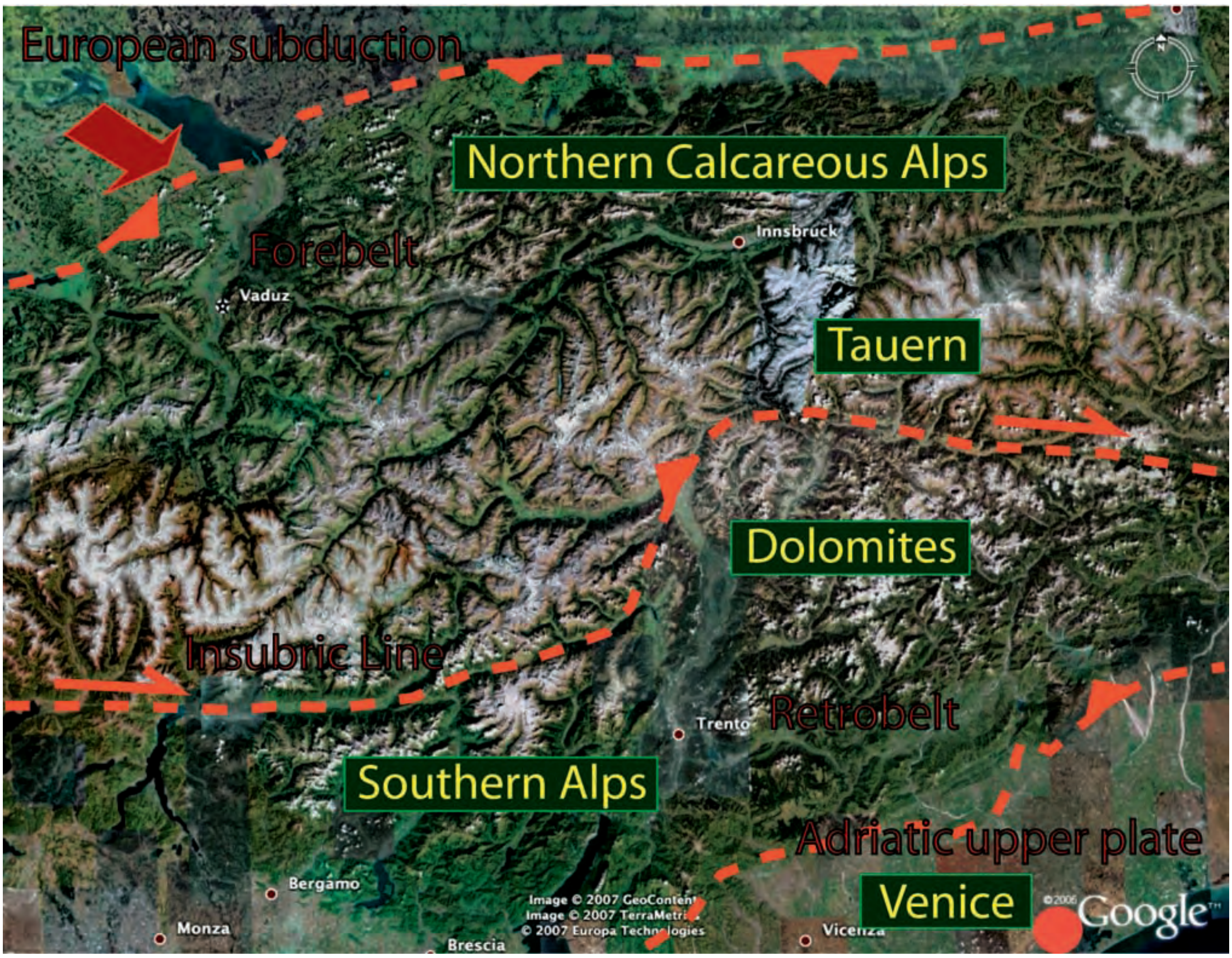


Fig. 227 - GoogleEarth map of the central-eastern Alps which formed by the subduction of the European plate beneath the Adriatic plate. The Dolomites are an element of the Southern Alps which constitutes the retrobelt of the Alpine orogen.

Late Ladinian magmatism. Early Jurassic rifting also controlled the subsidence which was larger in the eastern side of the Dolomites. This long period of generalized subsidence was followed by a pre-Neogene (Late Cretaceous-Paleogene?) ENE-WSW compression that generated a WSW-verging belt. This shortening amounts to at least 10 km. During the Neogene, the Dolomites as far north as the Insubric Lineament, were the innermost part of a S-verging thrust belt. The basement of the Dolomites was thrust southwards along the Valsugana Line onto the sedimentary cover of the Venetian Prealps for at least 10 km. This caused a regional uplift of 3-5 km. The Valsugana Line and its backthrusts on the northern side of the central Dolomites generated a 60 km wide pop-up in the form of a synclinorium within which the sedimentary cover adapted itself mainly by flexural slip often forming triangle zones. The shortening linked to this folding is about 5 km with Neogene thrusts faulting and folding the shallower WSW-verging pre-existing thrust planes. On

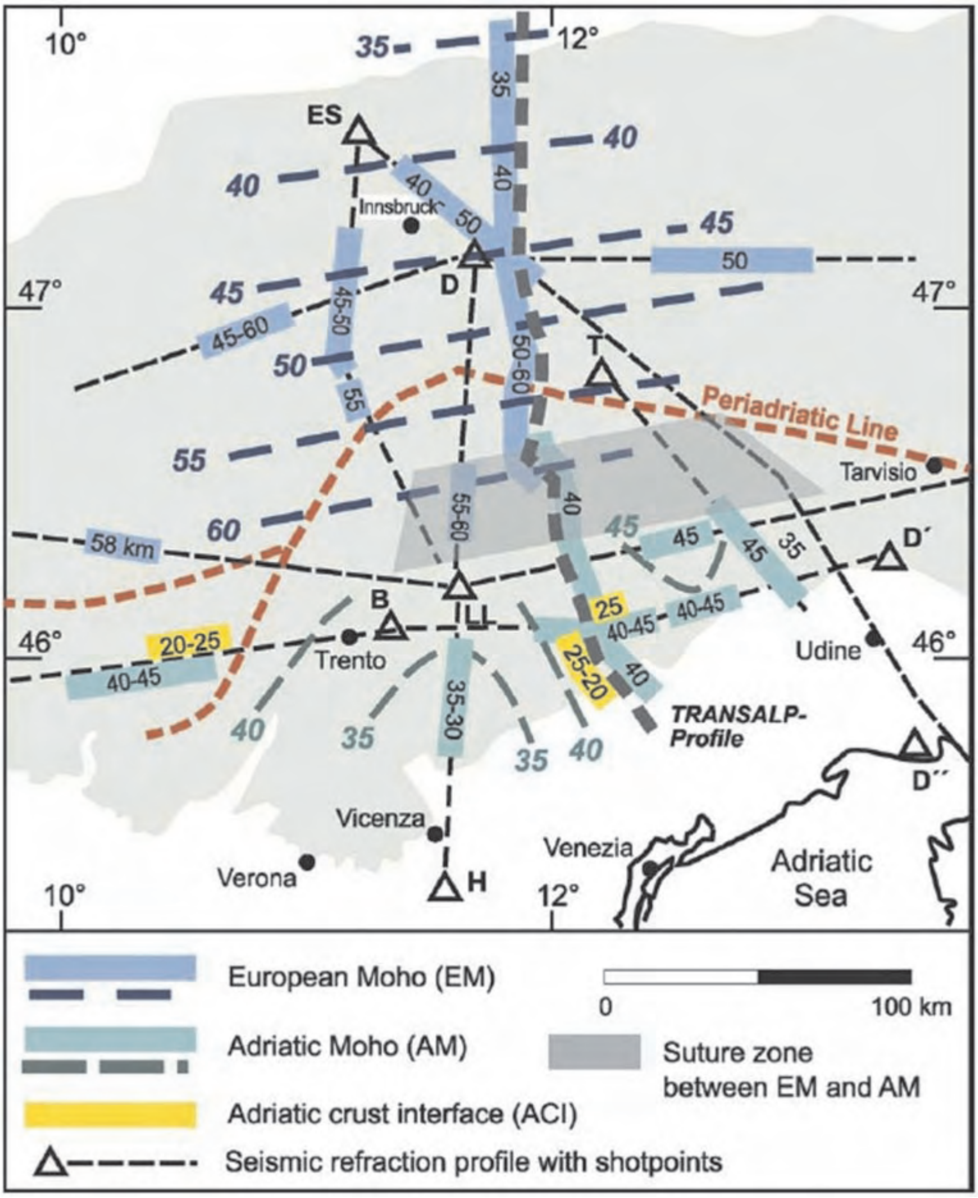


Fig. 228 - Moho depth in the central eastern Alps (after KUMMEROW *et alii*, 2004).

the north-eastern side of the Dolomites, Neogene deformation is apparently more strictly controlled by the transpressive effects of the Insubric Lineament (Pusteria Line) and shortening of the sedimentary cover may be greater than in the central Dolomites. Minor deformation linked to the Giudicarie belt is present in the western Dolomites. The eastern Dolomites are a recess of the earlier Alpine deformation where the ESE-verging Giudicarie system represents the left-lateral transpressive oblique ramp, and the WSW-verging Paleogene thrusts of the central eastern Dolomites are the right-lateral transpressive oblique ramp. The recess is located on the Permo-Mesozoic Trento Horst.

The present structure of the Dolomites is thus the result of a number of tectonic events of different significance and different strike. Only a 3-dimensional restoration can unravel the true structure of the area.

In the Dolomites, local compressive features of Middle Triassic age have been demonstrated by thrusts and folds cross-cut by volcanic dykes and plutonic bodies of Ladinian age and coeval sediments sealing these structures. The en-échelon distribution of grabens, folds and other structures suggest a left-lateral movement along the basement involving N70°-90°-trend, particularly along the Stava and Trodena Lines, continuing along the northern limb of the Cima Bocche Anticline.

Tectonic features of magmatic origin are also present in the Dolomites. The radial pattern of faults and of the Ladinian volcanic dykes in the central-western part of the Dolomites suggests the presence of a domal uplift, genetically related to emplacement of the coeval magmatism. Subsequent calderas and volcano-tectonic basins complicate these structures in the Predazzo and Monzoni areas, which are located along the aforementioned alignment.

N-S or NNW-trending thrust and fold axes, accompanied by a corollary of consistent mesostructures, support the presence of a ENE-WSW-directed compression. These tectonic features are widespread throughout all the central-eastern Dolomites and involve up to Lower Cretaceous rocks. In the area of Monte Parei, north of Cortina, a lower Miocene conglomerate unconformably overlies these features. The thrusts are mostly thin-skinned with detachment horizons in the evaporitic Upper Permian Bellerophon Formation, plus a number of other shallower weak layers.

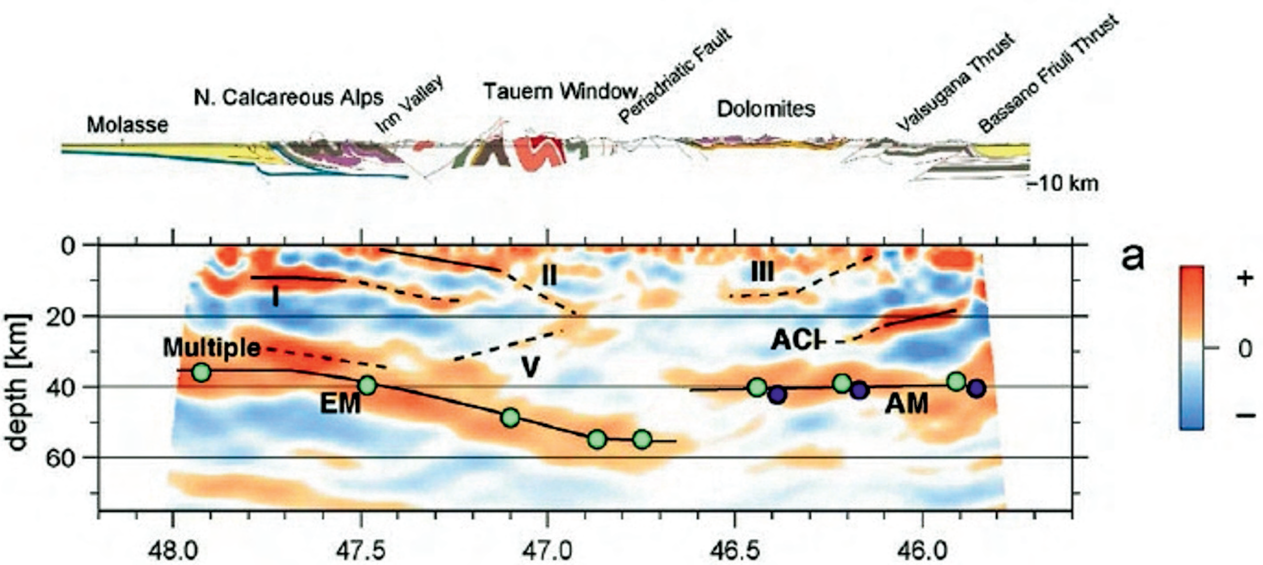


Fig. 229 - Evidence for the subduction of the European plate beneath the Adriatic plate from the TRANSALP profile in the central eastern Alps. EM, European Moho; AM, Adriatic Moho (after KUMMEROW *et alii*., 2004).

In a N-S section, the central Dolomites form a wide synclinorium (figs. 232, 233), genetically related to the Valsugana thrust in the south, and its N-verging backthrusts to the north (Funes and Passo delle Erbe Lines). Therefore, the Dolomites are within a pop-up-related syncline generated by the two conjugate thrusts. The Valsugana thrust to the south over Miocene sediments. The strike of Neogene thrusts and folds ranges from N90° to N50°. Conjugate strike-slip faults trend N30°-60°W (dextral transpression) and N0°-30° (sinistral displacement). Several valley in the central and northern Dolomites now lie along dextral strike-slip faults (e.g., Valparola, Valle di S. Vigilio). These strike-slip faults often show

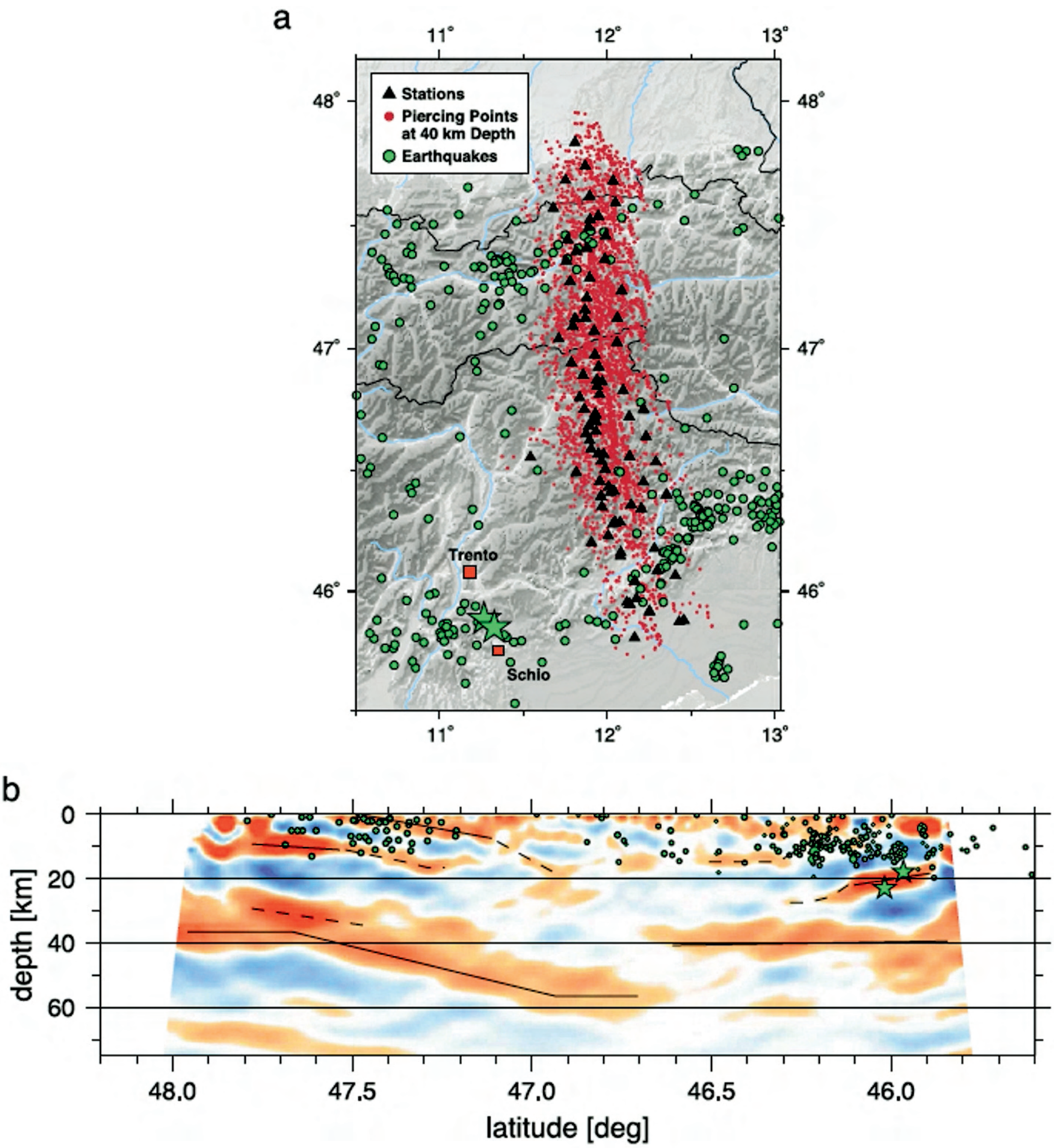


Fig. 230 - Seismicity distribution in the central-eastern Alps along the TRANSALP (after Kummerow et al., 2004). Note how seismicity is concentrated in areas of lower topography as suggested by Carminati *et alii* (2004).

both positive and negative flower structures. Neogene deformation generated most of the present elevation of the Dolomites, which form a slab of upper crust carried southwards by the Valsugana thrust.
The central Dolomites form the innermost part of the Southern Alps, the conjugate retro-belt of the Alpine subduction, where Europe subducted S-ward beneath the Adriatic plate. To the south of the Dolomites, the sedimentary cover of the Venetian Prealps is considerably shortened. In the central Dolomites, the sedimentary cover has rather been generally preserved, and the basement has been displaced southward by the Valsugana thrust for at least 8-10 km. The basement syncline, associated with the Valsugana thrust and the back-thrusts to the north, produced folding of the overlying sedimentary cover. The flower structures inherited from the Triassic times have complicated the core of the synclinorium. The sedimentary cover adapted itself to Neogene folding of the basement by generating semi-cyclindrically shape folds by flexural slip or flexural shear. Thus the Neogene compression of the Dolomites apparently did not generate strong shortening within the sedimentary cover apart from the adaptation to basement folding. Using an area balance, 10% (ca 5 km) Neogene shortening of the sedimentary cover in the central Dolomites, along a N-S cross-section, is about the same as that calculated by restoring the folding of the basement without taking into account inherited pre-Neogene structures (figs. 235 - 238).
Since the Dolomites stratigraphy contains a number of Triassic carbonate platforms and intervening basins, these inherited features represent mechanical discontinuities that influenced ramps and undulations of the thrust trajectories. The staircase trajectory of the thrusts is connected with marked differences in the rheological behavior of the different stratigraphic horizons.
The different tectonic phases of the Dolomites (figs. 239 - 268) formed mainly at low temperature (diagenesis) and are essentially brittle tectonics. However, Ladinian magmatism, Mesozoic burial and the Alpine event produced anchimetamorphic temperatures. Slow ductile behavior has been recognized for the Werfen Formation, and a temperature of about 200°, suggestive of anchimetamorphism conditions (Garzanti, 1985), has been proposed for Carnian sandstones in the western part of the Southern Alps.

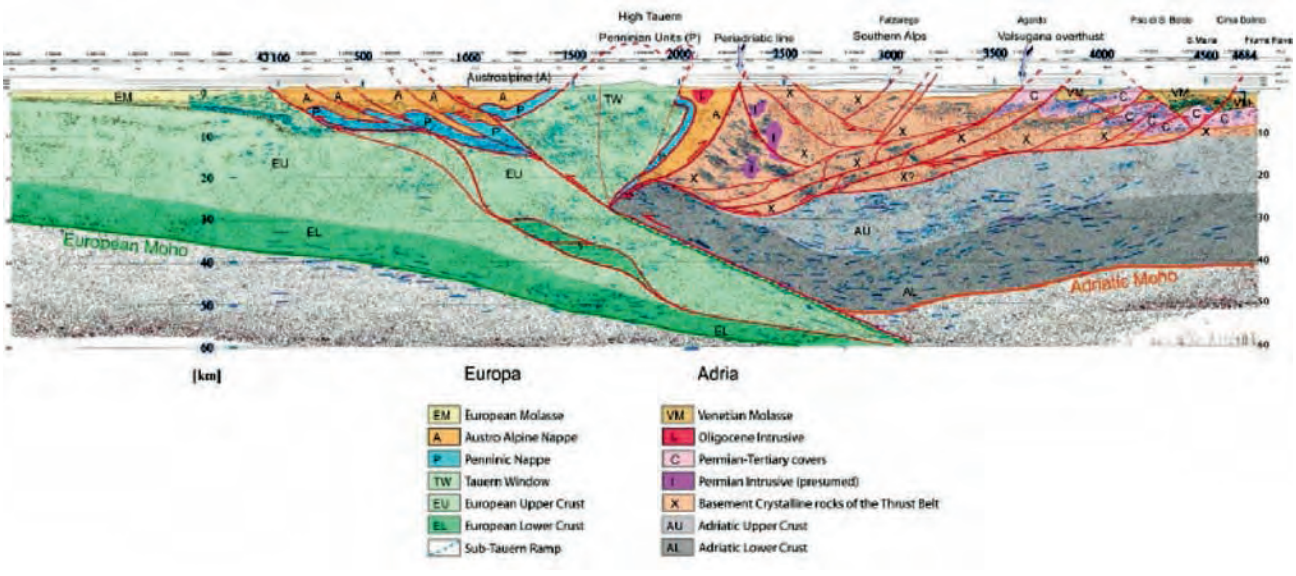


Fig. 231 - Interpretation of the TRANSALP profile after CASTELLARIN *et alii* (2006).

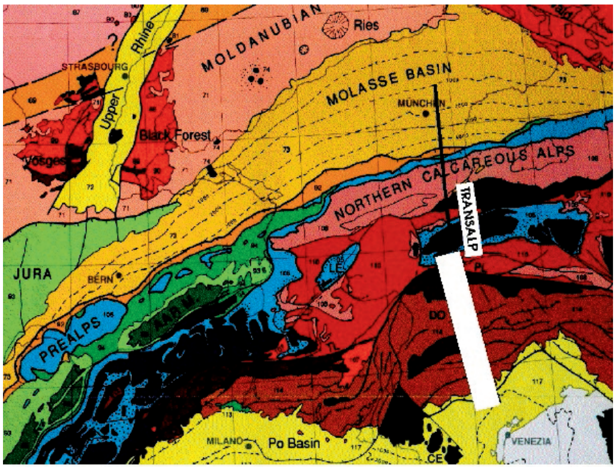
There are still doubts about the origin of the middle Triassic deformation and volcanism in the Dolomites. The models of an aborted rifting and the alternative interpretation of a ensialic subduction zone have been debated for long time.

Bob Goldhammer analyzed with incredible accuracy all the cycles of the Latemar carbonate platform, proposing an outstanding theory regarding their relationship with astronomical tuning (Goldhammer *et alii*, 1990). Their interpretation has been debated in a number of articles where the interior of the platform was dated in detail, indicating a too fast cyclicity for being astronomically correlated (Kent *et alii*, 2004).

The origin of the Middle Triassic tectonics and related subsidence in the Dolomites, coeval to the growth of the Ladinian carbonate platforms, has been interpreted in a number of ways, either as an aborted rift (e.g., Bechstadt *et alii*, 1977), or as an ensialic subduction zone (Castellarin *et alii*, 1979).

Whatever the origin of the Ladinian cycles is, in the Latemar massif they recorded a fast subsidence rate that can be estimated up to 600 m/Myr. This rate can be even higher in the eastern Dolomites, which subsided almost twice faster with respect to the western side from the Late Permian throughout the entire Mesozoic (e.g., Bosellini & Doglioni, 1986). Passive continental margin rates are generally much slower (even <50 m/Myr). The only extensional geodynamic setting where a subsidence rate similar to those recorded in the Latemar has been inferred is the backarc basin related to W-directed subduction zones (Doglioni, 1995).

W-directed subduction zones appear to nucleate along the retrobelt of pre-existing orogens related to E- to NE-directed subduction zones (Doglioni *et alii*, 1999). Examples are the Barbados subduction zone that developed along the retrobelt of the Central America cordillera, related to an E-directed subduction, and the Apennines, which started along the retrobelt of the south-westward prolongation of the Alps. East of the Dolomites there was the buried termination of the Hercynian retrobelt (e.g., Carnia, Friuli). Similarly to the quo-



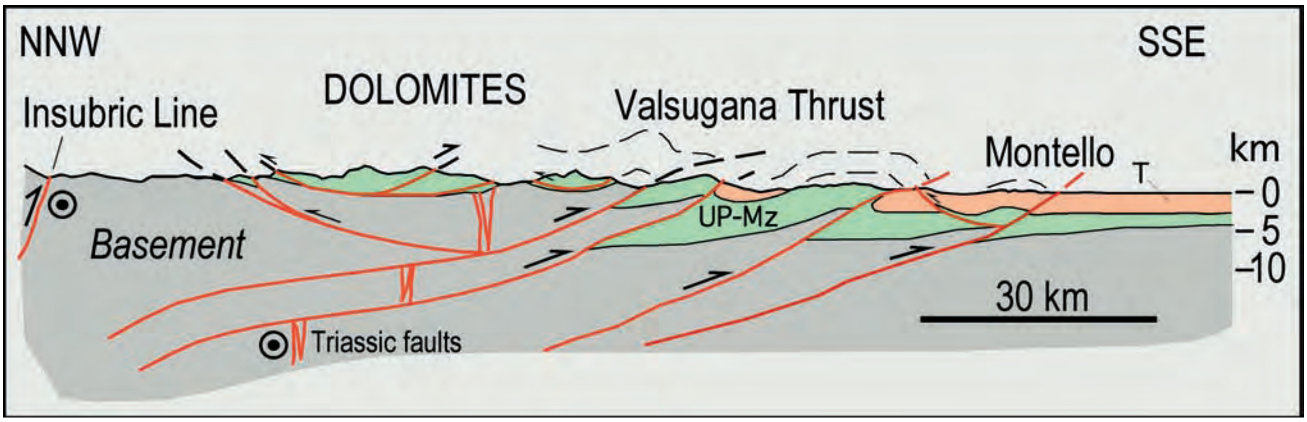


Fig. 232 - Cross-section of the Southern Alps along the southern segment of the Transalp (white thick line in upper map), modified after Doglioni, 1987. Map after Transalp Working Group. UP-Mz, Upper Permian-Mesozoic; T, Tertiary.

ted examples, if an oceanic or thinned continental lithosphere was occurring in the foreland of the Hercynian retrobelt during Late Permian or Early Triassic, a W-directed subduction zone could have taken place, retreating toward Slovenia, Hungary, being the relict of this hypothetic system now below the Pannonian basin. Therefore the Middle Triassic subsidence in the Dolomites is more compatible with a backarc setting of a W-directed subduction, and with the shoshonitic signature of the magmatic event that has been interpreted as subduction-related (PISA *et alii*, 1979).

Past plate motions in the Atlantic-Mediterranean-European realm have been reconstructed by a number of Authors (e.g., ZIEGLER, 1992; DERCOURT *et alii*, 2000). Since Paleozoic times, in the Atlantic area, E-W extension dominated, continuing with the Jurassic to Present oceanic spreading. To the east, the Cimmerian subductions system was NNE-directed. These reconstructions indicate an undulation in plate motions from E-W to NNE in the past, which persisted during the Cenozoic and is still active today. This basic and simple observation would support the presence of a tectonic mainstream of plate motions (DOGLIONI, 1993; CRESPI *et alii*, 2007) active both in the geologic past and today. The tectonic mainstream has a sort of tectonic "equator" that is at about 25° with respect to the geographic equator, pointing for a rotational component of plate tectonics, tied to the tidal effects (SCOPPOLA *et alii*, 2006). If this is true, plate motions are constrained by Earth's rotation now and in the past.

The Venetian part of the Southern Alps (N-Italy) is a Neogene south-vergent thrust belt located to the south of the Dolomites. The minimum shortening of the chain is 30 km. Most of the thrusts trend N60°-80°E and show an inherited N10°W-N10°E normal faults pattern of the Mesozoic continental margin. These earlier features strongly conditioned the evolution of the following oblique thrust belt. Structural undulations along strike of folds and thrusts occur in correspondence

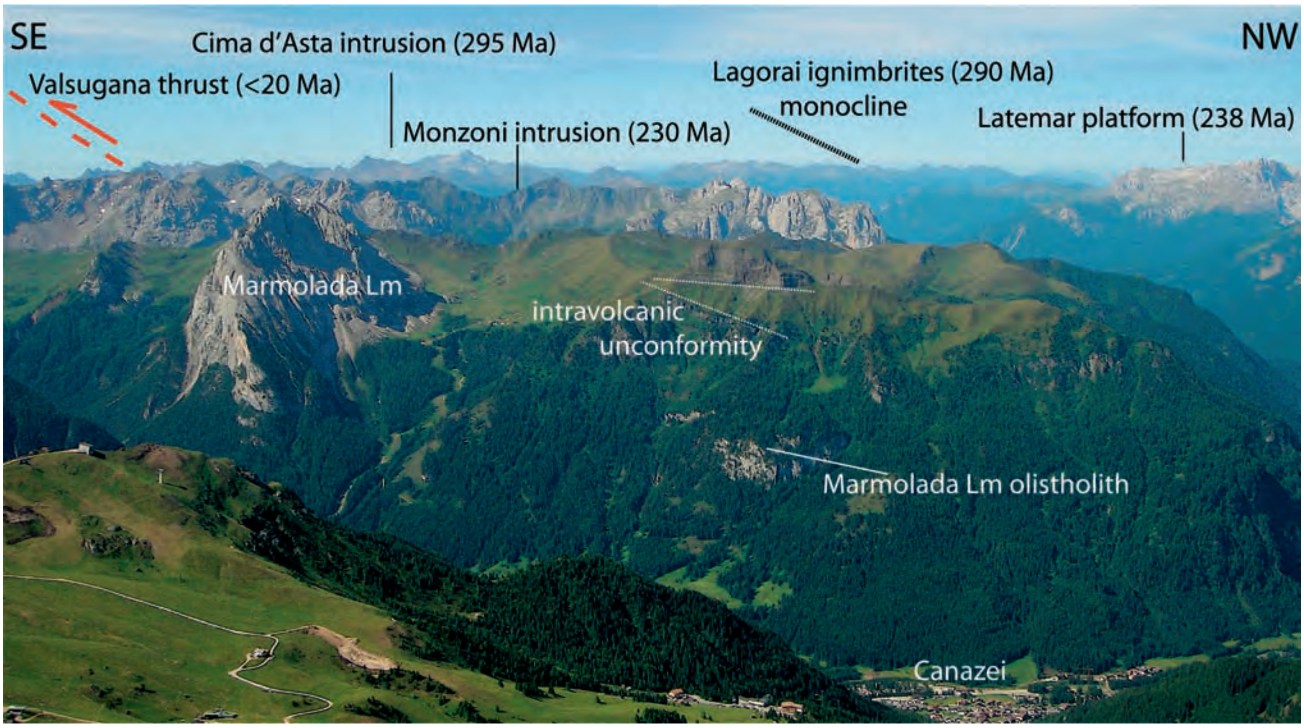


Fig. 233 - View of the southwestern Dolomites from the Sella Massif. The whole view is the southern limb of the Dolomites synclinorium, being the Lagorai monocline related to the ramp of the Valsugana thrust.

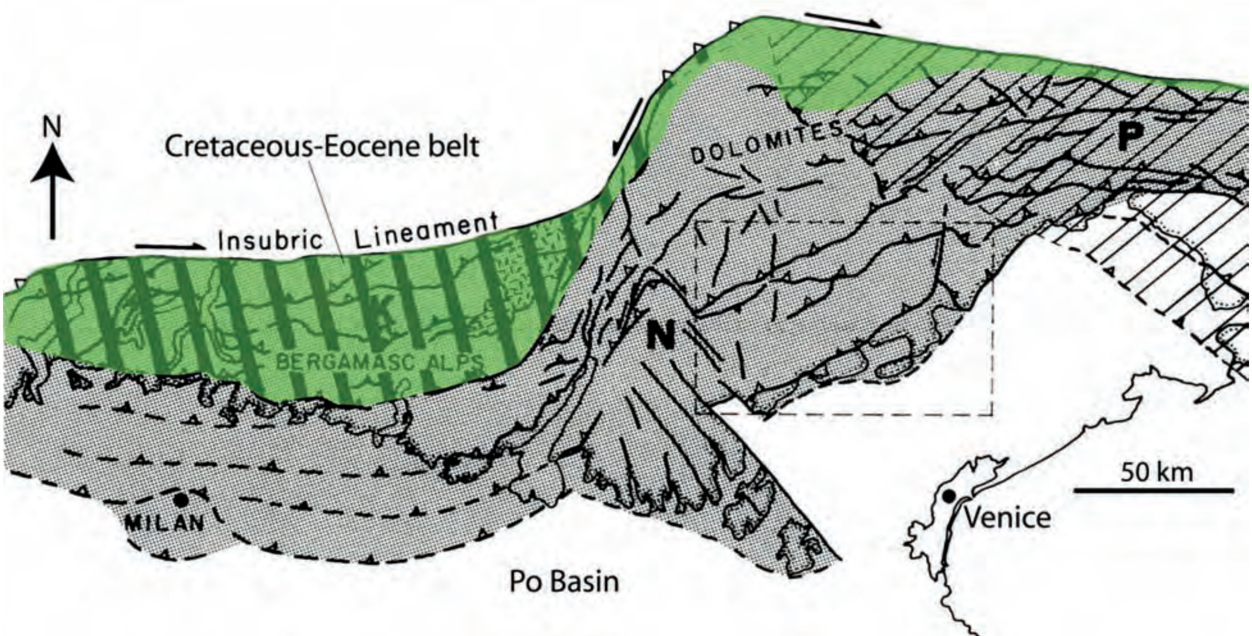


Fig. 234 - The Southern Alps underwent compressions at different times and in different areas. K: area of Late Cretaceous-Paleogene compression (green); P: Paleogene-Early Neogene compression (Dinarides); N: Paleogene-Neogene compression (Southern Alps). The rectangle indicates the area of the next figure which has been deformed only by the SSE-vergent Neogene Southalpine thrust belt and was located in the foreland of the Paleogene WSW-vergent Dinaric thrust belt. Note in the eastern side the overlap between Southern Alps and Dinarides.

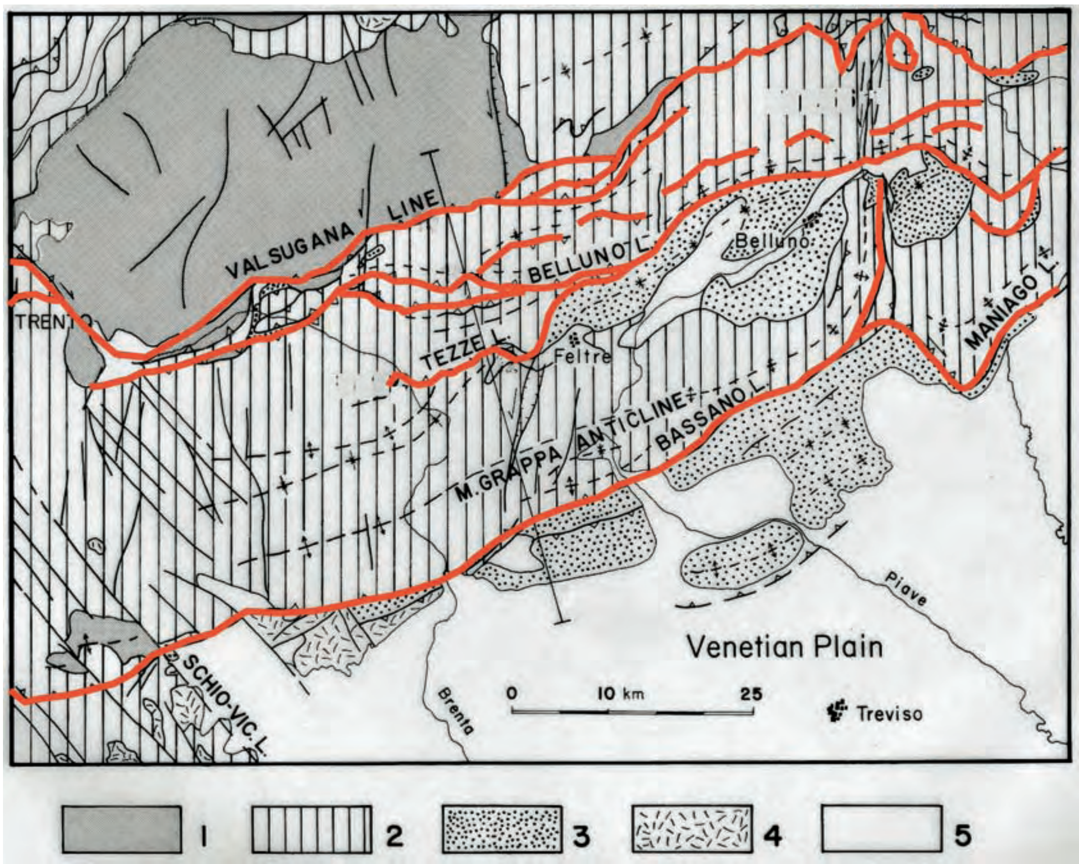


Fig. 235 - Simplified tectonic map of the Venetian Alps and location of the next section. 1) Hercynian crystalline basement and Permian ignimbrites; 2) Late Permian and Mesozoic sedimentary cover; 3) Tertiary sediments, Flysch and Molasse; 4) Triassic and Tertiary volcanics; 5) Quaternary. Red lines, thrusts.

to Mesozoic faults, thickness and facies variations. The thrusts are arranged in an imbricate fan geometry. A frontal triangle zone laterally ends at transfer faults. Earlier stages of the thrust belt were characterized by frontal triangle zones, which have later been involved and cut by the progression of the internal thrusts.

The Southern Alps were part of a Mesozoic continental margin, according to stratigraphic analysis, i.e. facies and thicknesses changes (BERNOULLI *et alii* 1979; WINTERER & BOSELLINI 1981). The area can be divided into three main structural sectors during Mesozoic. These are, from west to east: the Trento Platform, the Belluno Basin and the Friuli Platform. True Mesozoic normal faults (i.e. Liassic) have been documented at the western border of the Trento Platform (CASTELLARIN 1972; DOGLIONI & BOSELLINI 1987) and proposed also at the eastern margin (WINTERER & BOSELLINI 1981; BOSELLINI *et alii* 1981; BOSELLINI & DOGLIONI 1986; MASETTI & BIANCHIN 1987, DOGLIONI & NERI 1988).

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 main Mesozoic tectonic features bordering the Belluno Basin are from west to east: the eastern margin of the Asiago Plateau, the Seren (Graben) Valley, the Cismon Valley alignment (clearly seen on satellite images), the Passo Rolle Line, the S. Gregorio alignment, and to the east the Col delle Tosatte - Fadalto alignment. The Mesozoic alignments probably used inherited Variscan discontinuities as well. Platform and basinal Mesozoic facies do not coincide everywhere with the old horst and graben structure, i.e. the drowned Trento Platform, which acts as a horst with reduced basinal sequences after the Middle Jurassic until the Late Cretaceous.

The geometry of the thrust belt is that of an imbricate fan with a main envelop angle produced by the thrust slices close to 7° (critical taper of wedge). The main thrusts are from the internal parts to the foreland, the Valsugana Line, the Belluno Line, the Moline Line, the Tezze Line, and the Bassano Line. The thrust

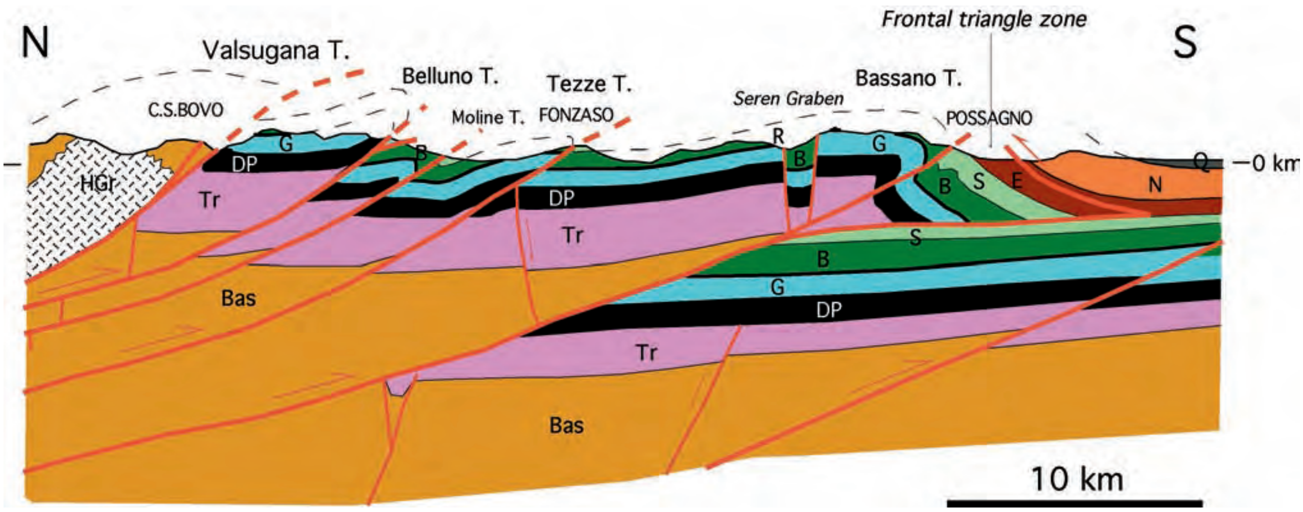
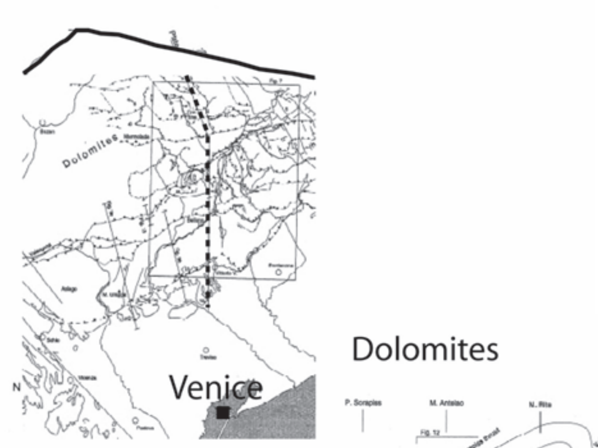


Fig. 236 - Balanced cross-section across the Venetian Alps. See Fig. 235 for location. Horizontal scale = vertical scale. Legend: Bas, crystalline basement; HGr, Late Hercynian granite; Tr, Late Permian-Lower and Middle Triassic formations; DP, Late Triassic (Dolomia Principale); G, Liassic platform facies (Calcari Grigi) gradually passing southward 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; thin black layer) B, Early Cretaceous (Biancone); S, Late Cretaceous (Scaglia Rossa); E, Paleogene (Possagno Marls, etc.); N, Late Oligocene-Neogene Molasse; Q, Quaternary.

belt is not cylindrical in shape and the strain continuously changes along strike. In a map view of the area, the thrusts show an anastomosing pattern along strike, maintaining constant shortening which can conservatively be calculated as 30 km.

The structural evolution of the thrust belt shows a general rejuvenation from the internal thrust to the external ones. However the internal thrust sheets seem to have been reactivated also in recent times (SLEYKO *et alii* 1987). The crystalline basement outcrops in the hangingwall to the Valsugana thrust, and is composed of Variscan metamorphosed greenschist facies rocks intruded by Late Carboniferous granitic bodies. Basement depth in the Venetian Plain is inferred by magnetic data (CASSANO *et alii* 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). The basement is clearly involved in the Valsugana Line, but balanced cross-sections would indicate a wider involvement by southern thrusts as well. We cannot exclude significant thickness variations of the sedimentary cover and minor dips of the thrusts which would considerably increase the amount of shortening along the thrust belt (ROEDER 1989). The main decollement of the thrust belt appears to be located in the basement (15-20 km in depth) beneath the Dolomites as suggested by the construction of balanced cross-sections (DOGLIONI 1987) and by focal mechanisms of earthquakes indicating low angle thrust planes (i.e. the Siusi event, SLEJKO *et alii* 1987). 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 correspondence of inherited features, i.e. the sinistral N0°-10°E striking transpressive undulation of Borgo Valsugana which occurs in correspondence of an inherited structural high as supported by the reduced thickness of the sedimentary cover. The thrust is generally in ramp and abandoning earlier staircase trajectories in the sedimentary cover probably due to the poor possibility to fold by flexural slip.



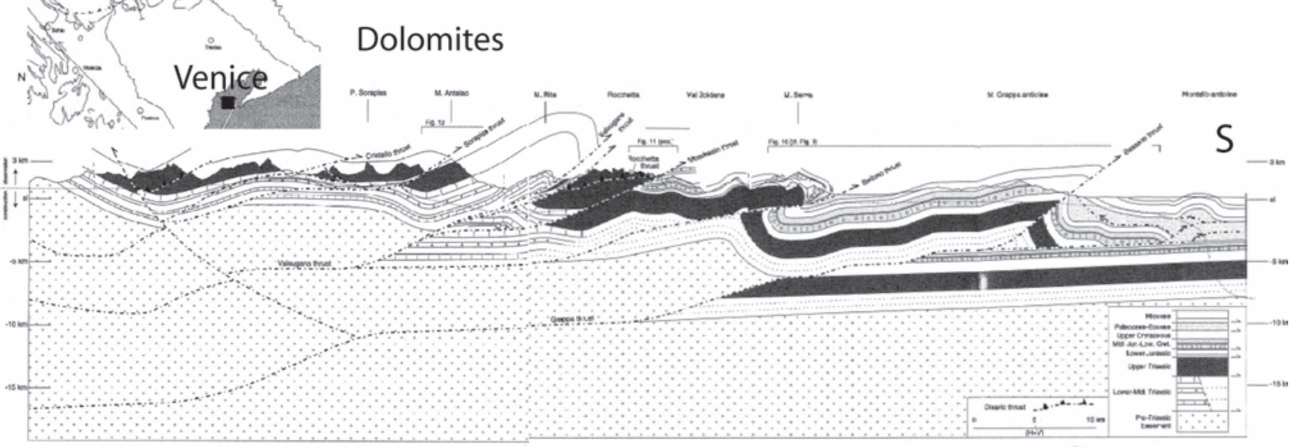


Fig. 237 - Cross-section of the Dolomites and eastern Venetian Prealps (after SCHÖNBORN, 1999).

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 accommodated 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 (fig. 238) which generates a general southward dipping mono-

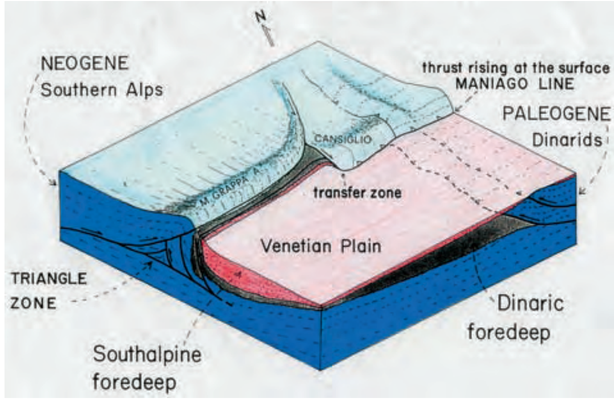


Fig. 238 - Schematic picture of the Venetian Alps front. The foothills are characterized by a triangle zone. The deep thrust plane (Bassano Line) reaches the surface (Maniago Line) through a transfer zone (Caneva Line). The Venetian Plain represents the foredeep of two opposite thrust belts. The geometry 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.

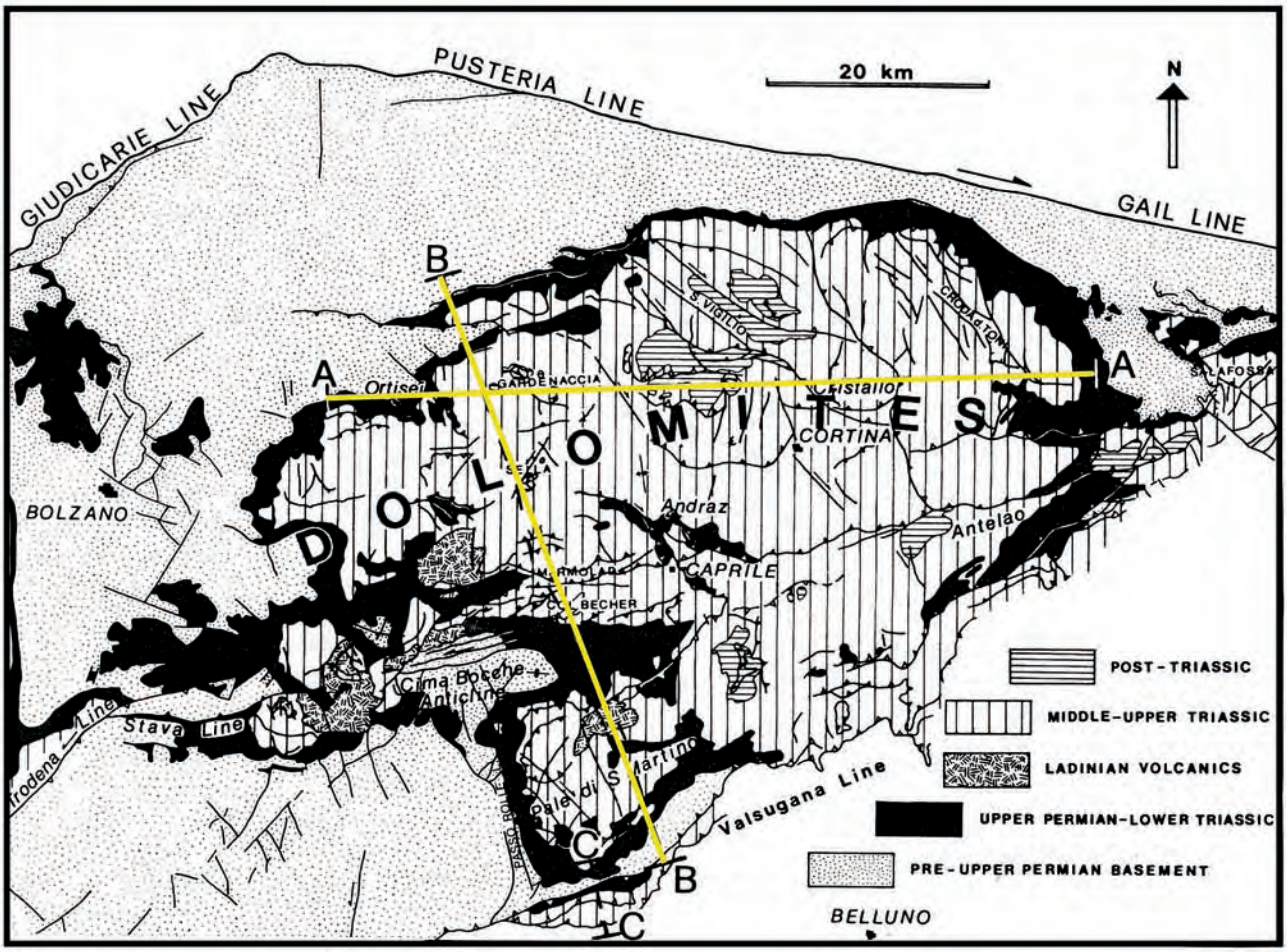


Fig. 239 - Simplified tectonic map of the Dolomites.

cline characteristic 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 alii* 1966; JONES 1982; BOYER & ELLIOTT 1982); 4) the presence of north-vergent backthrusts (i.e. in the Possagno and Follina areas, BRAGA 1970; ZANFERRARI *et alii* 1982).

It is interesting to note that a similar triangle zone has been reported for the northern part of the Alps in the Bavarian foreland (MÜLLER *et alii* 1988). The triangle zone between Bassano (Schio?) and Vittorio Veneto seems to be connected with a ramp-flat geometry of the deep seated blind thrust which generated a thrust-propagation fold (the Monte Grappa - 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 alii* 1986). 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). It is clear that the unconformities are angular only along dip where the frontal fold is perpendicular to the assumed regional maximum Neogene stress (sigma 1: N20°-30°W) and the fold axis presents a "cylindric" trend. Where there are structural undulations in the fold axis (i. e. the sinistral transpressive zones of Valdobbiadene-Cornuda and the greater Fadalto alignment) 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

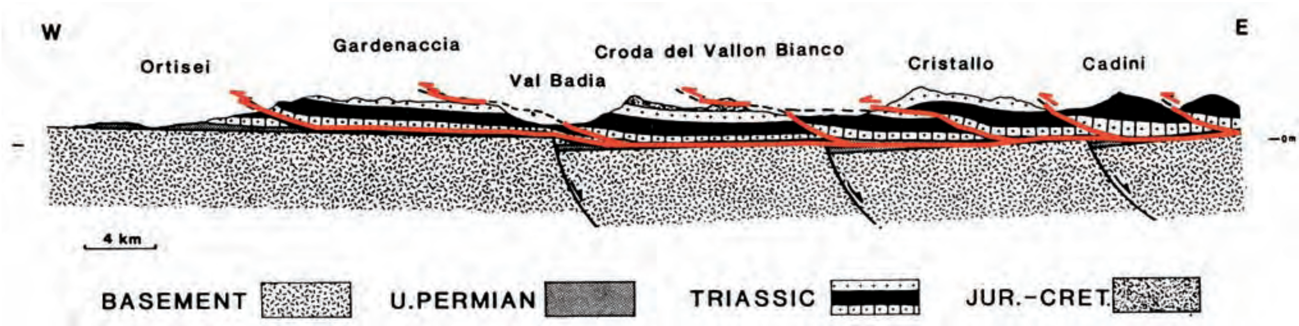


Fig. 240 - E-W cross-section of the Dolomites, showing WSW-vergence of thrusting. Location in figure 239.

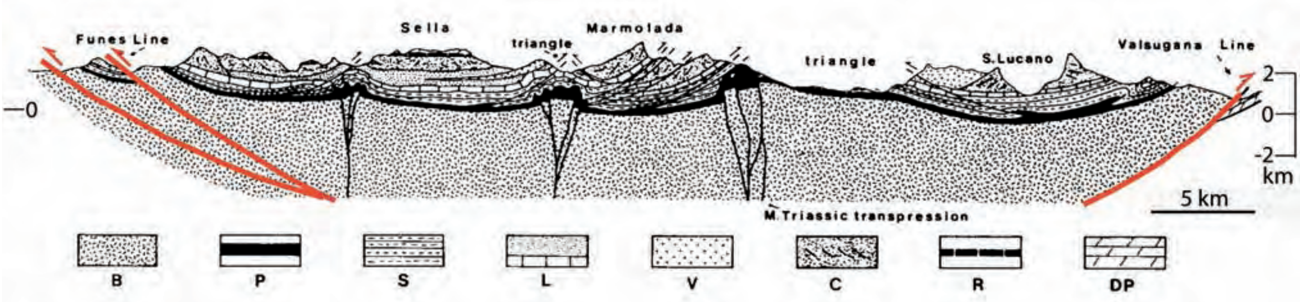


Fig. 241 - NNW-SSE cross-section of the Dolomites, showing the wide basement syncline generated by the pop-up. Location in fig- 239.

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.

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.

In the Venetian segment of the Alps the thrusts became active during Late Oligocene to Quaternary times. Tortonian sandstones are thrust by the Valsugana Line (VENZO 1939) and Pliocene shales are folded along the frontal triangle zone. Moreover Messinian-Pliocene onlap geometries in the southern border of the chain support a mainly Neogene age of the deformation. The extension of the unconformities within the molasse is a function of the thrust belt structure and reflects areas of stronger uplift. A problem is represented by the style and timing of the orogenic evolution: has the chain southward regularly risen in a continuum creep since Late Oligocene time and do the unconformities record moments of sea level fall (low stand)? Or was the chain generated step by step so that the unconformities simply mark moments of tectonic crisis? In general, plates move with a regular velocity suggesting that in areas of deformation the tectonic evolution should follow an almost constant activity. If the tectonic evolution generated with a constant regularity and tectonic crisis had a wavelength too short or too long with respect to the eustatic sea level changes, then an interesting problem appears in dating the thrust belt: the timing of

Fig. 242 - Croda del Vallon Bianco, northwest of Cortina. The thrust is WSW-verging and mainly Jurassic Calcari Grigi outcrop both in the hangingwall and in the footwall. The geometry of the hangingwall cut-off allows to reconstruct the undulated geometry of the fault plane.

the tectonic crisis has been considered as the time missing at regional unconformities and the age of coarse-grained sediment supply (i.e. the Messinian Conglomerate) onlapping the discontinuity. But if the unconformities recorded only moments of general lowstand (in this case global or confined to the salinity crisis in the Mediterranean area) then we could argue that the chain developed more gradually and that the sea level oscillations orchestrated the arrangement of the syntectonic sedimentary sequences. The different interpretations of the unconformities and conglomeratic supply in the molassic sequences allow different tectonic reconstructions. With the sea level change interpretation (VAIL *et alii* 1977) the chain rises constantly during Late Oligocene-Neogene times, but if we assume the unconformities and conglomeratic supply to be tectonic-related, then episodic tectonic activity existed, which is in contrast to the regular activity of the frontal growth fold and the general plate motion.

In the Belluno syncline an angular unconformity marks the Early Eocene Flysch - Late Oligocene Molasse contact. Moreover the Flysch seems to onlap the northern limb of the Belluno syncline and to the west the Seren Valley alignment. Consequently we cannot exclude that the area underwent compressive tectonics already during Paleogene times.

The basement and the sedimentary cover of the region were broken by N-S trending normal faults and N60°-90°E transfer faults (the paleo-Valsugana Line ?) during the Late Permian-Mesozoic rifting phases. These features have been cut, reused or deformed during the alpine inversion. Local structural undula-

Fig. 243 - Upper Oligocene-Lower Miocene conglomerate (MP) at Mt. Parei - Col Bechei, to the northwest of Cortina, sealing an angular unconformity with the underlying Liassic Calcari Grigi (CG) deformed by WSW-verging thrust and folds. This outcrop dates active pre-Late Oligocene WSW-verging shortening in the Dolomites.

tions 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 is arranged in approximately 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

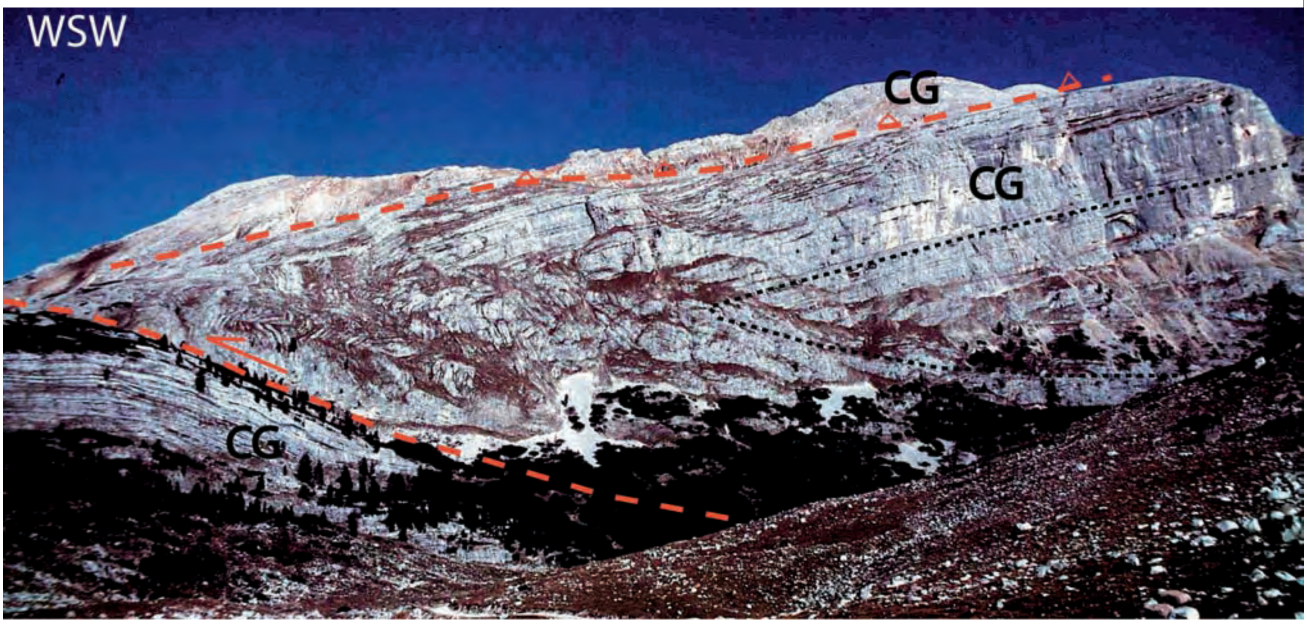


Fig. 244 - Col Bechei western side. The overturned fold in the hangingwall of a WSW-verging thrust, has been later cross-cut by a S-verging thrust. See following figure. CG, Liassic Calcari Grigi.

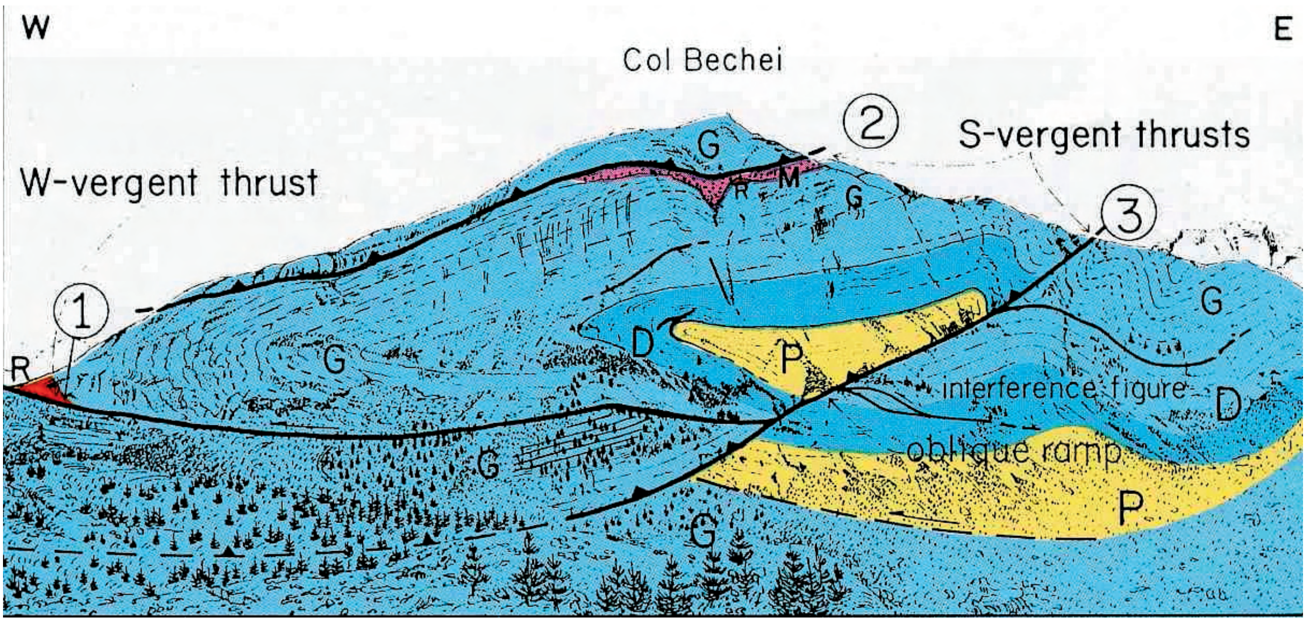


Fig. 245 - The Col Bechei structure, northwestward of Cortina. The WSW-verging thrust (1) is sealed by the Upper Oligocene Mt. Parei conglomerate. The thrust and the related fault-propagation recumbent fold are cross-cut by the later S-verging alpine thrusts (2, and 3). Numbers refer to the kinematic sequence. The two almost orthogonal compressive phases generated an interference structure. P, Dolomia Principale (Norian); D, Dachstein Limestone (Rhaetian); G, Calcari Grigi (Liassic); R, Ammonitico Rosso (Dogger-Malm); M, Mt. Parei Conglomerate (Oligocene-Miocene). After DOGLIONI & SIORPAES (1990).

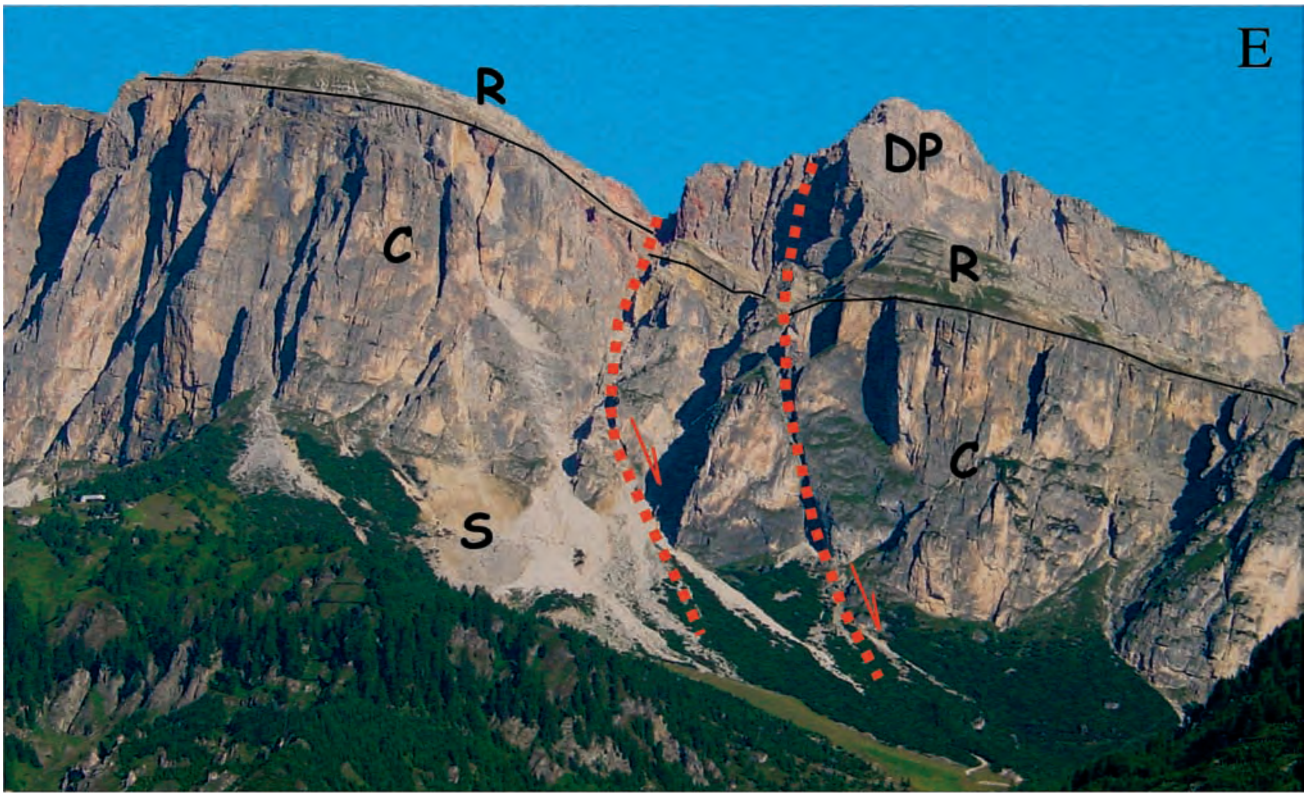


Fig. 246 - Southern view of the Puez-Gardenaccia Massif, showing N-S trending listric normal faults, above Colfosco, in Val Badia. The faults dip to the east and cut the succession up to the Dolomia Principale. They are somewhere accompanied by reddish oxidations and by sedimentary dykes. The grass ledge corresponds to peritidal deposits of the Dürrenstein or Raibl Fm. Legend, DP, Norian Dolomia Principale; R, Upper Carnian Raibl Fm; C, Lower Carnian Cassian Dolomite; S, San Cassiano Fm. Compare with the section of fig. 251 where the above shown tensional structures are represented below Gardenaccia.

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). The deformation at the western end of the Valsugana Line is transferred in the Trento area through the dextral transpressive Calisio Line to the sinistral transpressive Giudicarie Belt to the west. This undulation once again runs around a minor inherited Late Paleozoic and Mesozoic horst, within the wider Trento Platform. 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. The Alpine deformation within the Belluno Basin is more diffuse, characterized by a larger number of thrust planes and reduced wavelength folds with respect to the lateral platform areas. The Belluno Line mainly develops to the east of the Trento Platform. It branches the Valsugana thrust and shows an eastward increase in displacement and amplitude of the fault-propagation folding and fault-bend folding in the hangingwall. Commonly, the inherited tensional Mesozoic areas have been reactivated in transpressive zones and are transfer zones between two different styles of deformation. For instance the N-vergent backthrust in the hangingwall of the Belluno Line ends at the western margin of the Vette Feltrine at the intersection with the inherited

tensional zone of the Cismon Valley. The Caneva Line and the Fadalto Line are dextral and sinistral transpressive zones respectively at the eastern margin of the Belluno Basin. The Caneva Line represents the eastern transfer fault of the frontal triangle zone. The Fadalto transpression was emplaced at the western termination of the Friuli Platform. The study area was located in the foredeep of the Dinaric thrust belt during Paleogene times and suffered subsidence due to the load of the WSW-vergent Dinaric thrust sheets. A regional ENE-dipping monocline developed at that time and was inherited and involved in the younger SSE-vergent Neogene Southalpine deformation. The variations along strike of the deformation are reflected also in the Neogene and Quaternary foreland basin.
The good outcrops and the clear interference between inherited features and Alpine tectonics make the Venetian Alps a classic example of thrust belt. Earlier Mesozoic features strongly influenced the evolution of the chain. Any kind of structural undulation along strike of the thrust belt is associated with pre-existing synsedimentary faults, thickness and/or facies variations in the sedimentary cover. The thrusts are arranged in an imbricate fan geometry and show a frontal triangle zone which was probably present at earlier stages of the thrust belt in more internal zones. The variations along strike of the deformation are reflected also in the Neogene and Quaternary molasse. The frontal triangle zone appears to be a growth fold rising from Late Oligocene to Quaternary times because clastic sedimentation on the southern limb of the anticline shows onlap geometries and reduced thicknesses. According to this progressive evolution of the thrust belt, the unconformities within the molasse could record lowstands of eustatic cycles.
The effects of four independent Neogene to

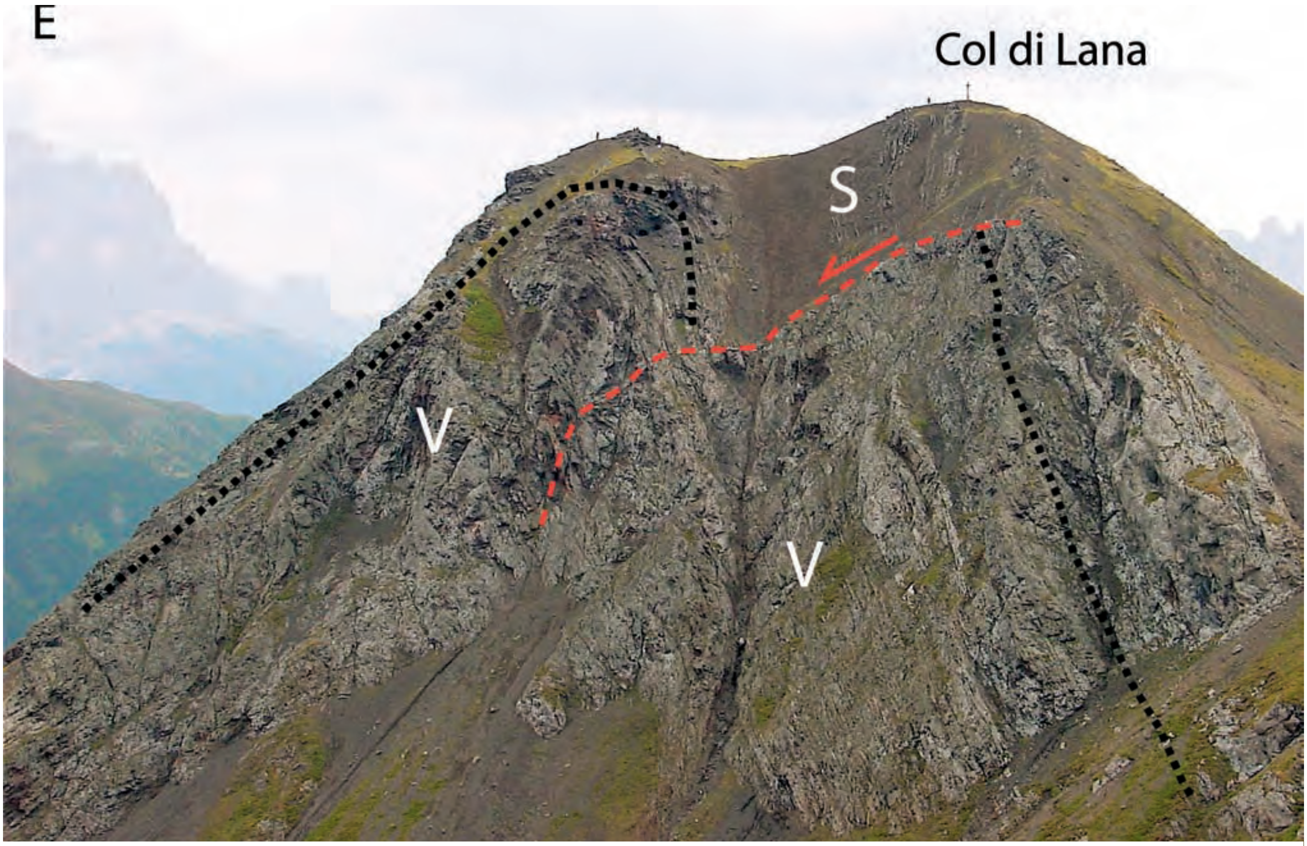


Fig. 247 - Example of a W-verging anticline inheriting a normal fault of Mesozoic(?) age at the top of the Col di Lana, central Dolomites. V, Upper Ladinian volcaniclastic sandstone; S, Lower Carnian San Cassiano Fm.

present subduction zones coexist in northeast Italy:
1) The dominant one is the Alpine subduction, where Europe subducted the Adriatic plate, and the Southern Alps are its related retrobelt.
2) The Alpine belt overlapped/interfered with the frontal thrust belt of the Dinarides, where the Adriatic plate rather subducted the Eurasia plate.
3) Moving eastward, normal faults of the Pannonian backarc basin of the Carpathians subduction crosscut the Northern Dinarides and part of the Eastern Alps.
4) The hinge retreat of the Apennines subduction determines subsidence of the entire NE-Italy.
All these indicate that separate geodynamic settings can co-work in a given area, and their related stress fields may interact or overlap simultaneously.
1) The Transalp section (TRANSALP, 2002) confirmed the main double vergent structure of the Alps. It shows no N-S extension in the Alps, excluding significant orogenic collapse as

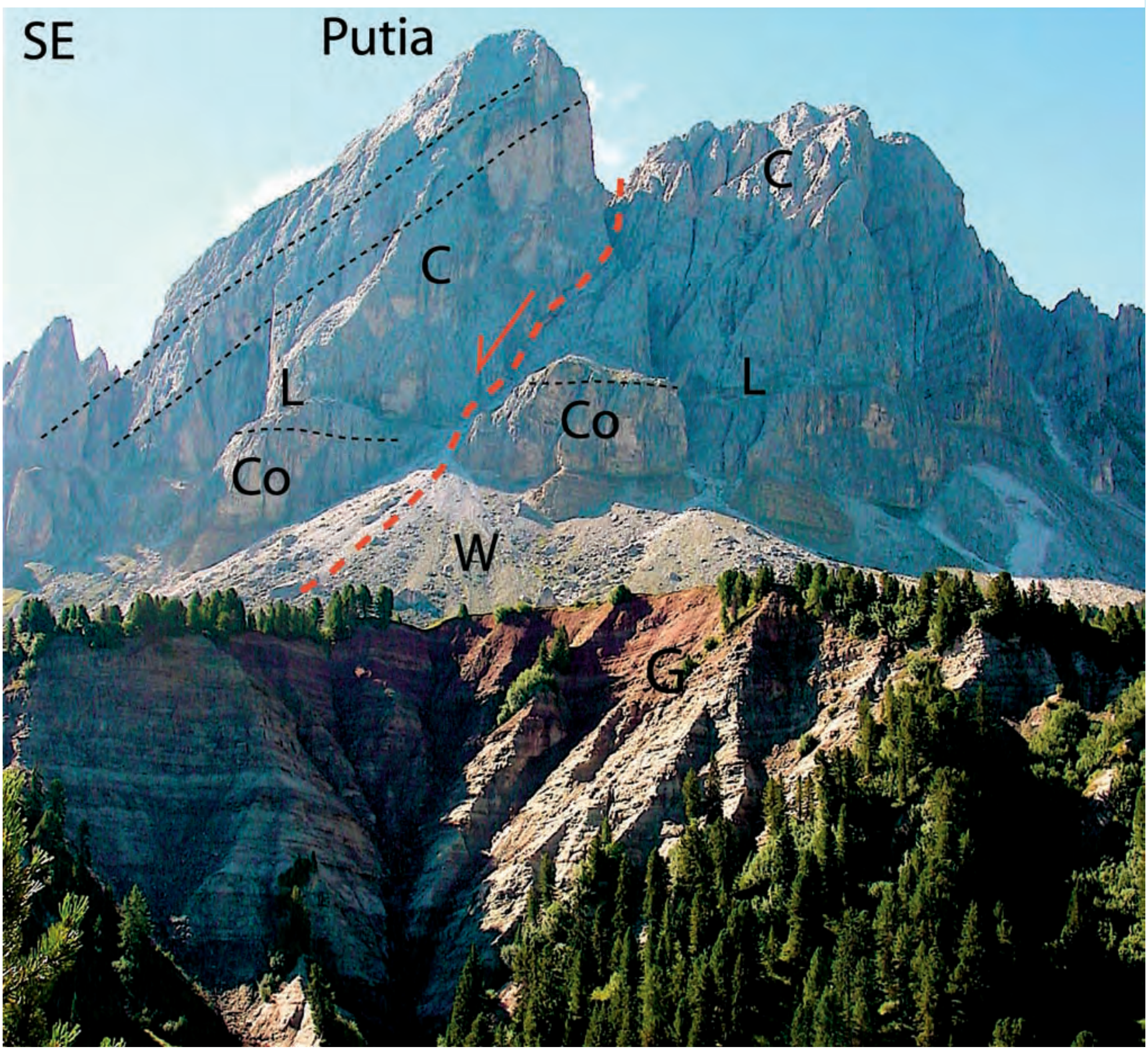


Fig. 248 - Northeastern slope of the Sass de Putia, northern Dolomites. A N-S trending normal fault lowers the eastern side of the massif. C, Marmolada Limestone; L, Livinallongo Fm; Co, Contrin Fm; W, Werfen Fm; G, Gardena Sandstone.

frequently proposed for orogens. The Southern Alps are notoriously bounded to the north by the right-lateral transpressive Insubric Lineament, but they are also considered the part of the orogen where the vergence of the thrusts is toward the subduction hangingwall, i.e., the Adriatic plate. Therefore, according to this second interpretation, the Southern Alps would extend in part also to the north of the Insubric Lineament, since several thrusts and folds present southward vergence. Pre-collision stage subduction zones exhibit well-developed retrobelts, such as the SubAndean belt, or the Rocky Mountains in the Southern and Northern America Cordilleras respectively. These analogues would suggest that the retrobelt in the Alps could have started since the early stages of the subduction.

2) The Dinarides and the Alps merged to generate a single belt in the Eastern Alps, but they remained two separated geodynamic processes, due to two independent subduction zones. It is important to distinguish their meaning and kinematic overlap of the related thrust sheets. WSW-verging thrusts enter the Dolomites section of the Transalp profile.

3) The Carpathians subduction probably followed the same geodynamic scenario of the Apennines, which started to develop along the retrobelt of the Alps where in the foreland to the east there was oceanic or thinned continental lithosphere, like the W-directed subduction zones of the Barbados and the Sandwich arcs in the Atlantic ocean (DOGLIONI *et alii*, 1999). According to this interpretation, the Carpathians developed along the retrobelt of the northern Dinarides, such as the Balkans in the south, where oceanic or thinned continental lithosphere of the Dacide basin was located to the east of the retrobelt. The consumption of this basin accompanied the E-ward retreat of the subduction to the present position in Vrancea. This implies that in the Pannonian basin there are elements of both Alps and Dinarides stretched and scattered.

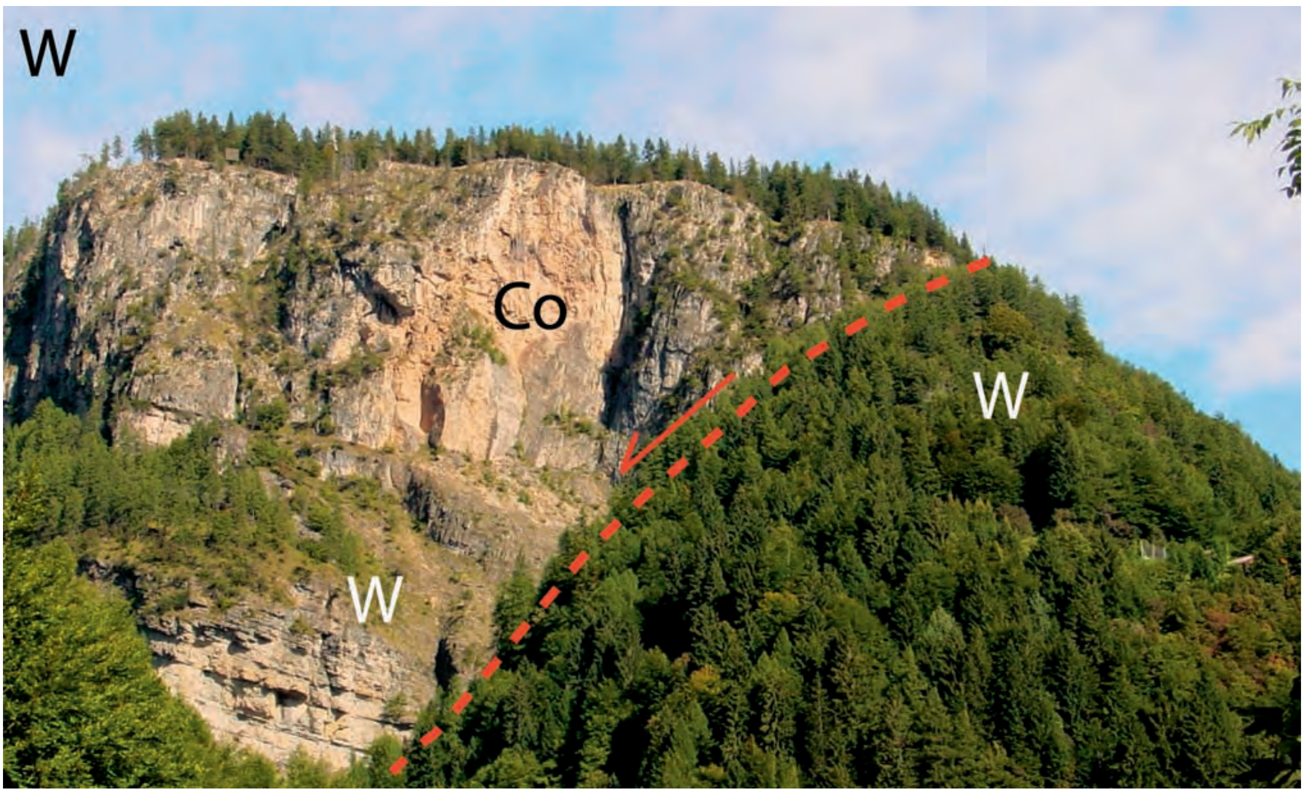
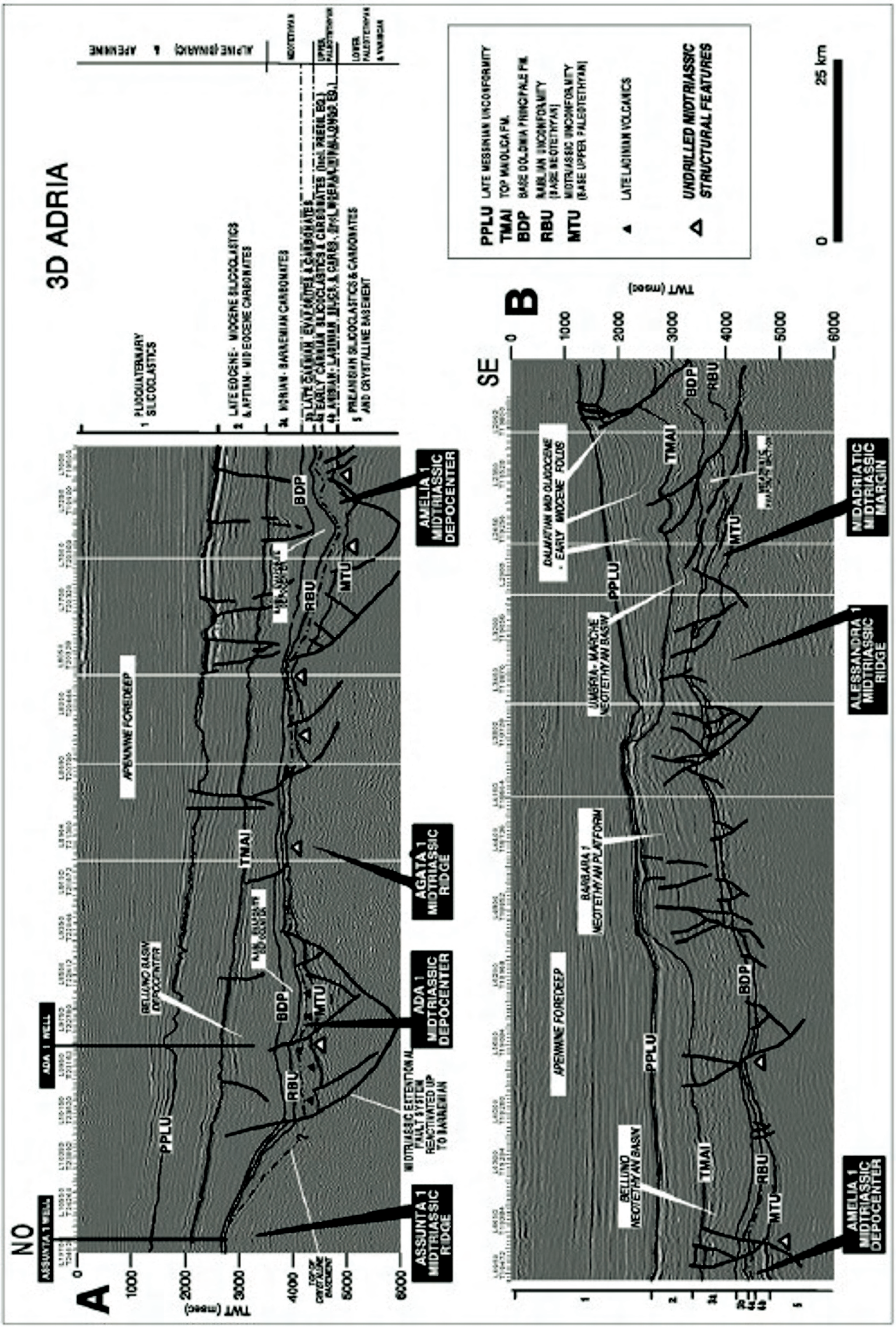


Fig. 249 - N-S trending normal fault likely of Mesozoic age outcropping near Cencenighe. Co, Contrin Fm; W, Werfen Fm.


3D ADRIA
A
NO
ASSUNTA 1 MIDTRIASSIC RIDGE
ADA 1 MIDTRIASSIC DEPOCENTER
AGATA 1 MIDTRIASSIC RIDGE
AMELIA 1 MIDTRIASSIC DEPOCENTER
APENNINE FOREDEEP
PPLU
TMAI
BDP
RBU
MTU
TWT (msec)
B
SE
ALESSANDRA 1 MIDTRIASSIC RIDGE
MIDADRIATIC MIDTRIASSIC MARGIN
PPLU LATE MESSINIAN UNCONFORMITY
TMAI TOP MAIOLICA FM.
BDP BASE DOLOMIA PRINCIPALE FM.
RBU RAIBLIAN UNCONFORMITY (BASE NEOTETHYAN)
MTU MIDTRIASSIC UNCONFORMITY (BASE UPPER PALEOTETHYAN)
LATE LADINIAN VOLCANICS
UNDRILLED MIDTRIASSIC STRUCTURAL FEATURES
0
25 km

4) Since the Paleogene, the Venetian and Friuli plains underwent subsidence due to the load of the Alpine and Dinarides thrust sheets, forming two related and anastomosed foredeeps. However, the thinning of the Pliocene-Quaternary sediments (MERLINI *et alii*, 2002), and the decrease of the regional monocline dip moving away from the Apennines front (MARIOTTI & DOGLIONI, 2000), they indicate an active subsidence all around this belt. The Apennines foreland subsidence affected most of the Alps and external Dinarides. The long-term subsidence of Venice and other coastal cities appears determined by the retreat of the subduction hinge of the Adriatic plate dipping underneath the Apennines. The flexure of the subduction hinge affects areas more than 250 km far to the northeast of the Apennines front, providing data on the viscoelastic behavior of the Adriatic plate continental lithosphere. Slab rollback of such a continental lithosphere can only be ascribed to the

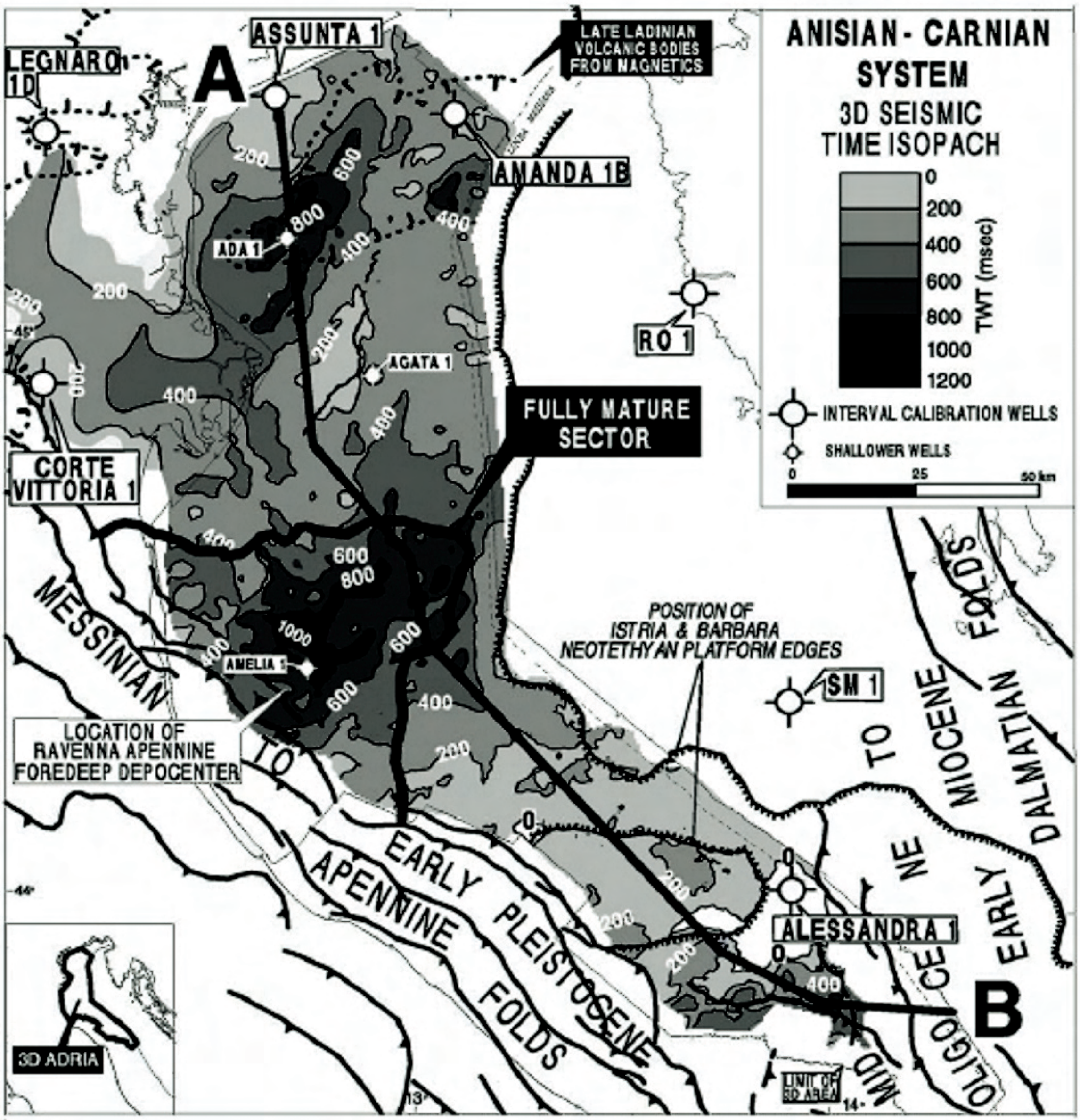


Fig. 250 - Evidences of Middle Triassic rifting in the Adriatic Sea, comparable to what outcropping in the Southern Alps. Front page, compressed random 3D seismic profile crossing the North Adriatic Mid Triassic depocenters and ridges. Above, two-way time isopach of Northadriatic Anisian-Carnian section. The mapped interval extends from the Midtriassic Unconformity to the base of Dolomia Principale, thus including the Late Carnian evaporite seal. After FRANCIOSI & VIGNOLO (2002), EAGE.

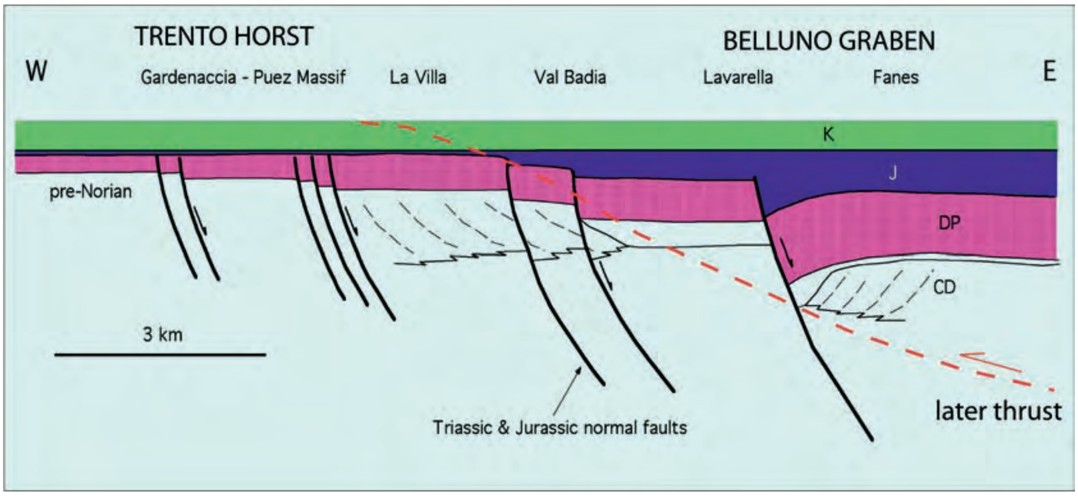


Fig. 251 - Paleotectonic section of the central-northern Dolomites between the Trento Horst to the west, and the Belluno graben to the east. All Mesozoic formations thicken moving eastward, suggesting active normal faulting at the hinge between the structural high and the low throughout the Triassic and Jurassic. Note how the extension and the differential subsidence is distributed in a number of normal faults, each one with relatively small offset. K, Cretaceous; J, Jurassic; DP, Norian Dolomia Principale; CD, Carnian Cassian Dolomite. Notice their regular spacing and the occurrence of the Calcari Grigi only to the east (to the west the Jurassic J is represented by the Ammonitico Rosso). The extensional fault system seems to have been active also during the Triassic, as suggested by the westward thinning of the Dolomia Principale (P) and of the underlying sedimentary section. Also the Raibl Fm changes its facies and thins toward the west. K, Puez Marls Fm, Cretaceous. The WSW-vergent thrusts developed as ramps along inherited extensional zones, or a platform margin.

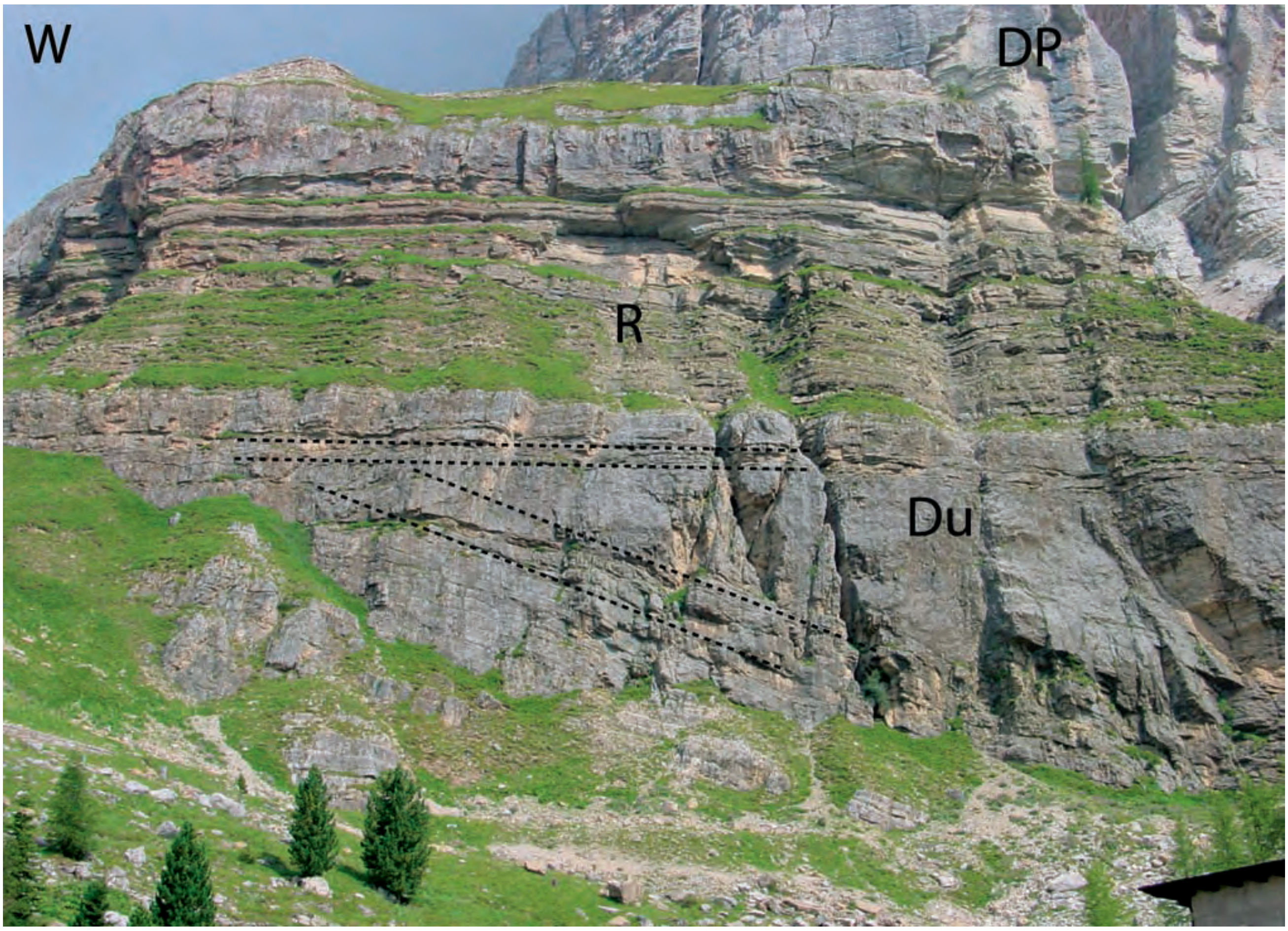


Fig. 252 - Angular unconformity between the Dürrenstein Dolomite (Du) and the overlying Raibl Fm (R) at the Rifugio Di Bona, beneath the Tofana Massif. DP, Dolomia Principale.

"eastward" relative mantle flow and not to slab pull.

Northeast Italy is usually interpreted as the area of N-S compression due to the African-Adriatic indenter. However, this comes from a misleading kinematic approach, where local stress field is assumed to be an indicator of plate motion. Stress field deviates along oblique plate margins, and the WNW-ward motion of the Adriatic plate relative to Europe can generate right-lateral transpression and consequent NW-SE to N-S compression along the central-eastern Alps. Moreover, the Adriatic plate and Europe, in an "absolute" reference frame (HEFLIN *et alii*, 2002), are both moving NE-ward, instead of N-S. European and Adriatic plates have different N-S component, but they move between 45°E and 52°E absolute directions.

The relatively high topography of the Alps is consistent with crustal scale thrusts (DOGLIONI, 1987; 1992; PFIFFNER *et alii*, 1997; Schönborn, 1999; Transalp Working Group, 2002), similarly to those observed in the Wind River thrust in Wyoming (ALLMENDINGER *et alii*, 1983). In spite of the elevated topography and more than 50 km thick continental crust (KISSLING, 1993), the Alps, both in the frontal belt to the north and in the conjugate retrobelt to the south, present low dip of the foreland regional monocline (3°-5°), typical of "E"-directed subduction zones, in contrast with the Apennines, due to a "W"-directed subduction zone, where associated to low topography the monocline is at places even steeper than 20° (MARIOTTI & DOGLIONI, 2000). As a general rule, salients of the thrust belt in the Alps and adjacent orogens occur along inherited Mesozoic basins. Therefore the several transfer zones are related to pre-existing structural and stratigraphic lateral variations of the passive margin architecture (e.g., platform to basin transition, N-S trending horsts and grabens). Moving along strike from the Transalp section, thrust belt transfers occur mainly through lateral variations of the ramp distance.

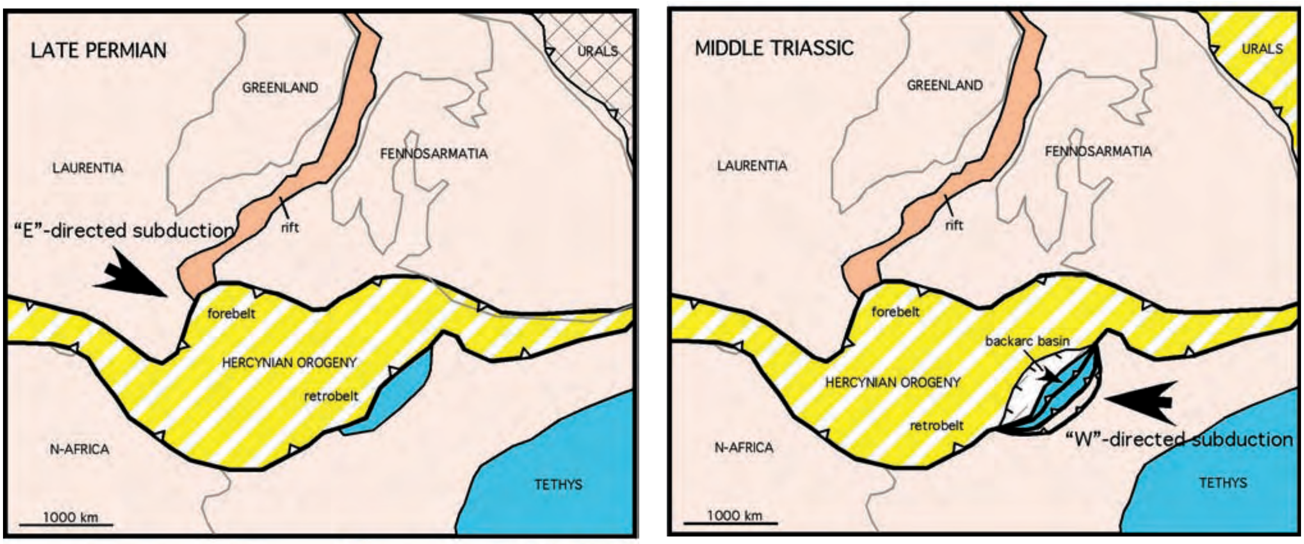


Fig. 253 - As in modern examples, where W-directed subduction zones developed along the retrobelt of an opposite subduction zone, the Middle Triassic of the Dolomites could have recorded the backarc rifting of such a setting. The Hercynian orogen was probably a collage of different subductions zones, but in general shows the characters of E-directed subductions zones, as the double vergence. If a small oceanic embayment was located east of the Hercynian retrobelt during Late Permian or Early Triassic, then a W-directed subduction zone could have developed, generating fast subsidence rate in the backarc basin (e.g., >600 m/Ma, Middle Triassic Southern Alps), and the shoshonitic magmatism.

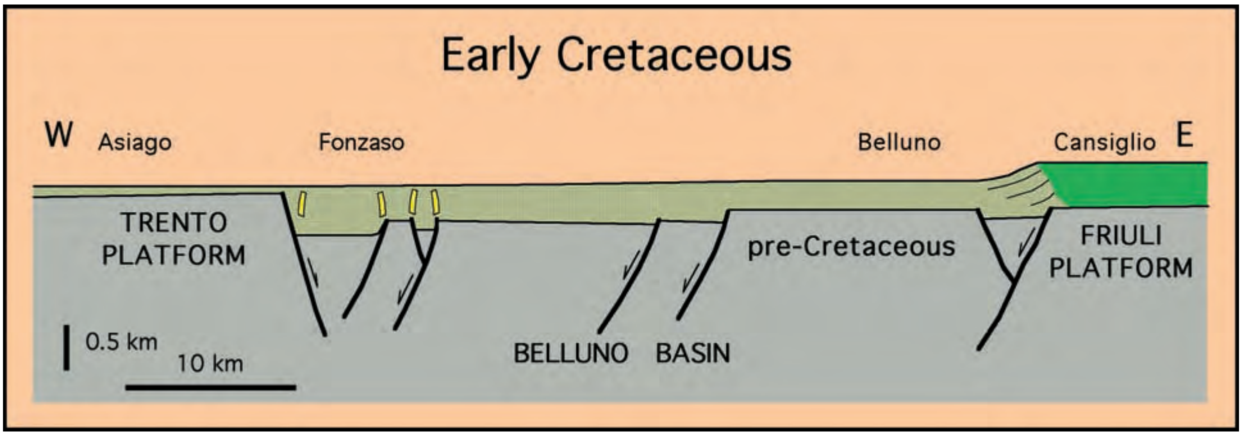


Fig. 254 - Interpreted W-E Early Cretaceous cross section from the Asiago plateau to the Cansiglio plateau, showing the coeval tensional tectonics, which produced differential subsidence in the area. Note the basinward prograding carbonate platform in the eastern side (M.Cavallo Limestone) and the different thicknesses in the basinal sedimentation (Biancone). Neptunian dikes (vertical yellow segments) characterize the zones of tensional tectonics (i.e. the Arsiè Lake, Fonzaso). The Neogene deformation has been strongly influenced by the pre-existing structural and stratigraphic geometries. See location and compare the general tectonics of the area with the inherited Mesozoic structural background in fig. 149.

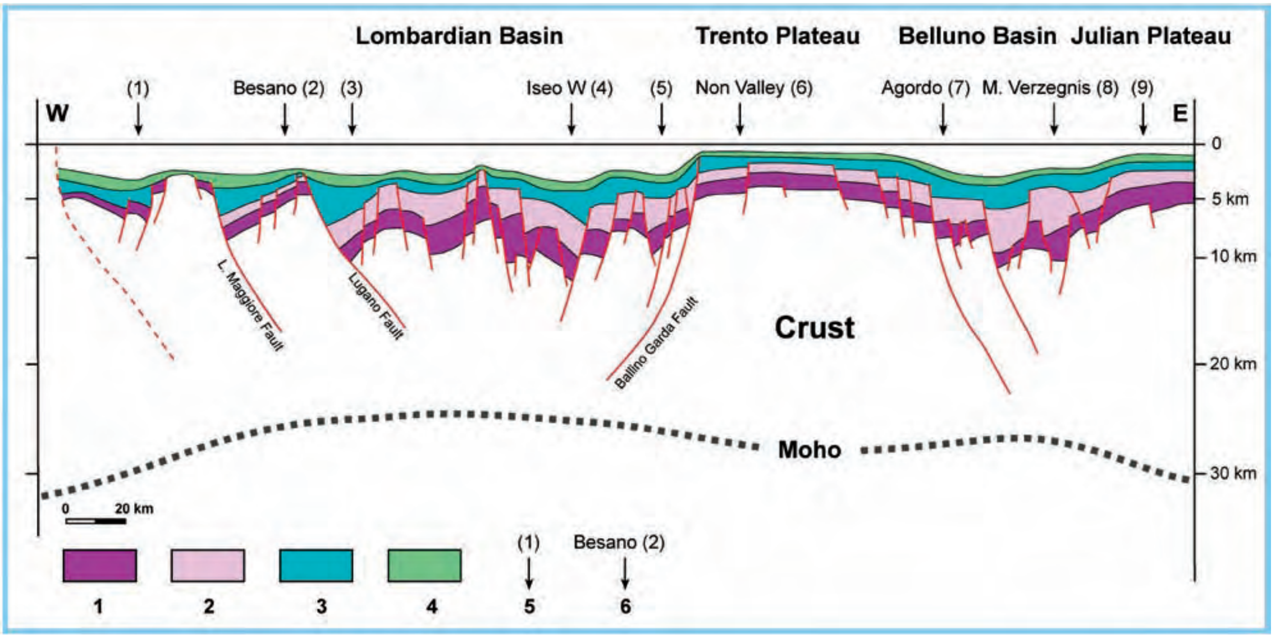


Fig. 255 - Extensional Mesozoic architecture of the Southern Alps at the end of Lower Cretaceous time. 1) Permian - Carnian p.p.; 2) Carnian p.p. - Rhaetian; 3) Hettangian - Bajocian; 4) Bathonian -Aptian pp.; 5-6) Location where samples have been collected for organic matter maturity analyses and for thermal modelling (after Fantoni & Scotti, 2003). The Upper Cretaceous crustal structure in only speculative and does not reflect the present day crustal thicknesses, which have been increased by the Alpine compressional tectonics.

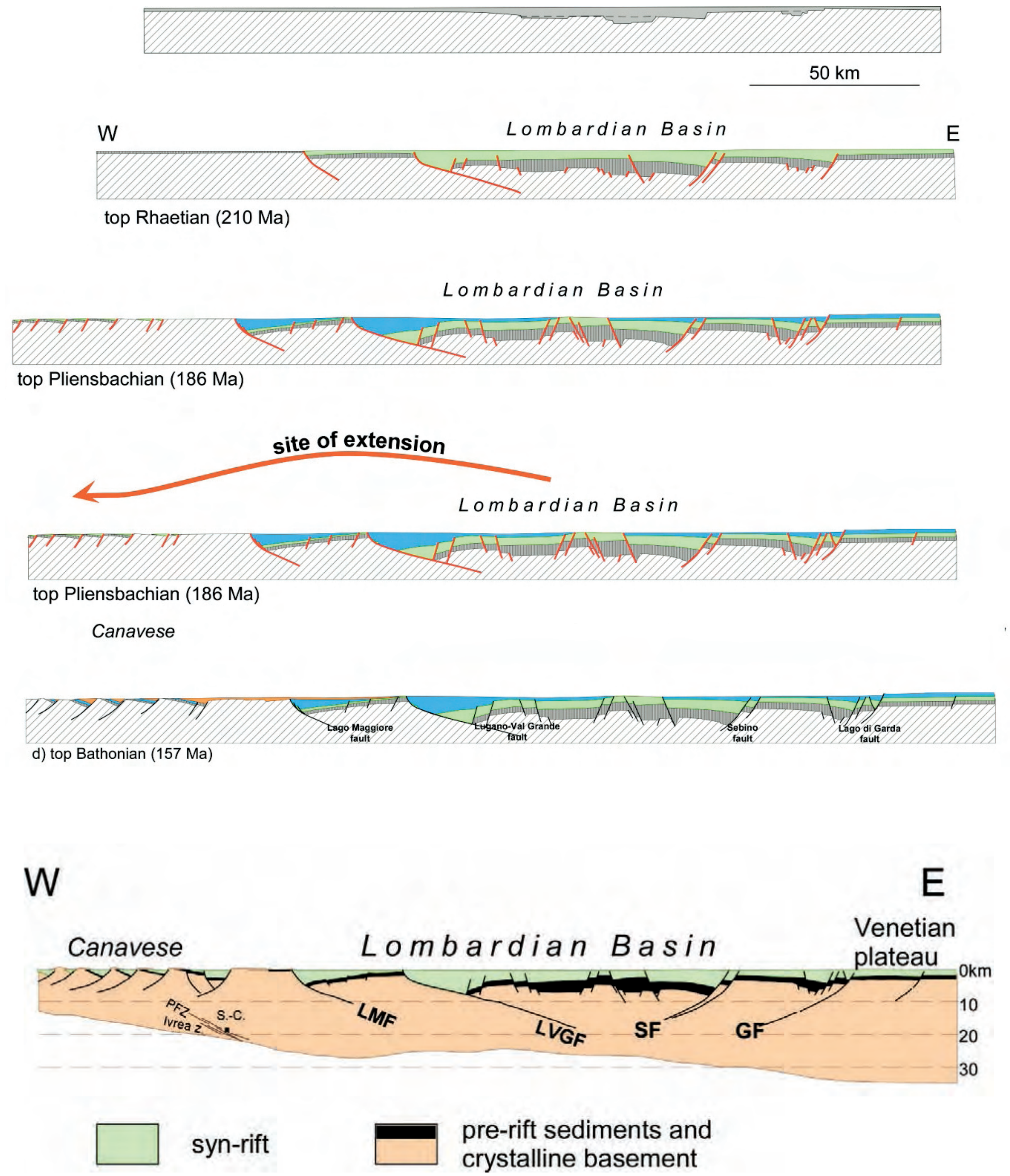
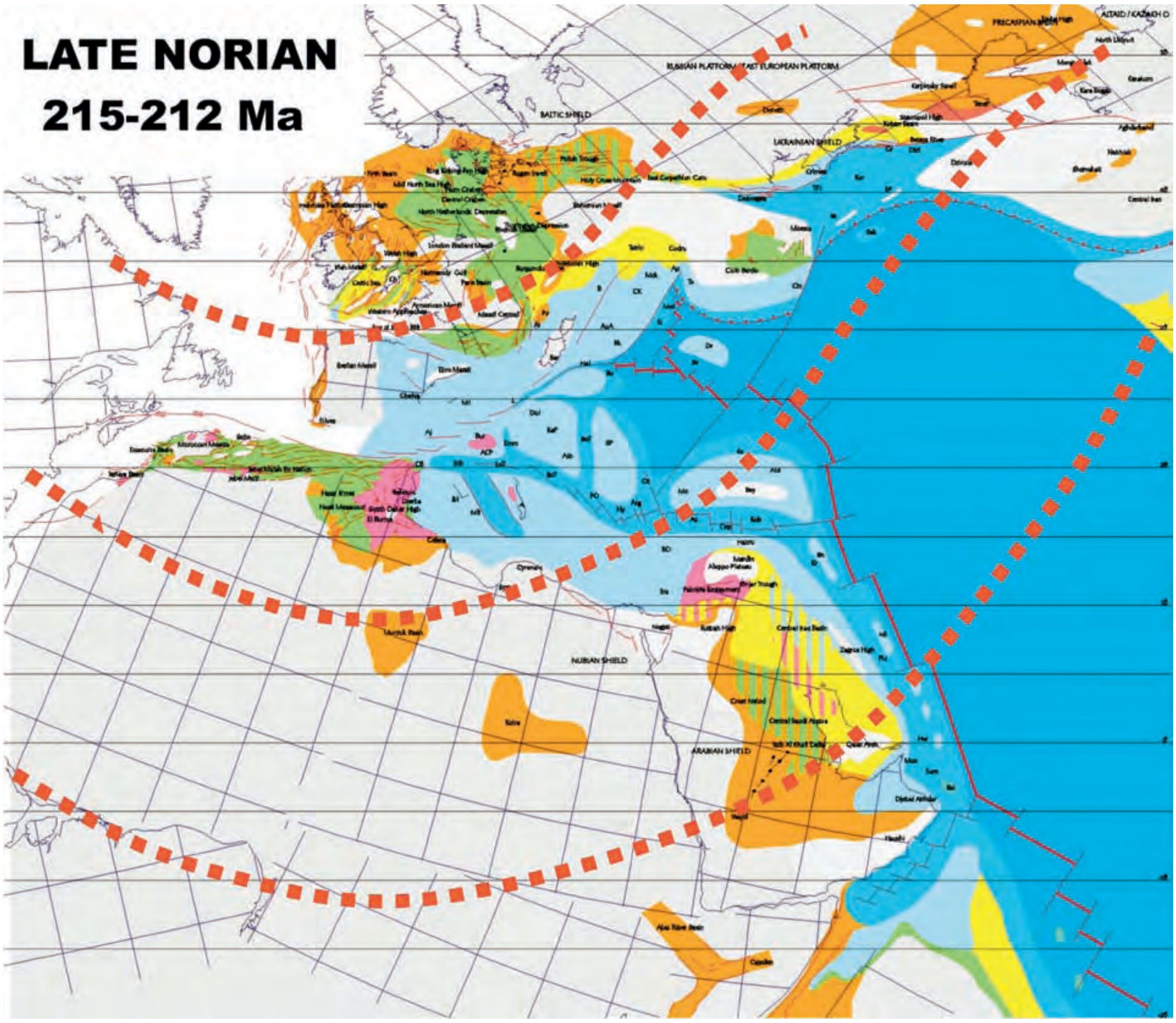


Fig. 256 - Recontruction of the Late Triassic-Jurassic rifting in the central-western Southern Alps (after BERTOTTI *et alii*, 1993). The Venetian Plateau represents the Trento Horst.



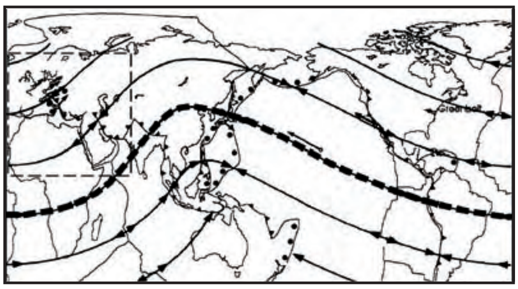


Fig. 257 - Panel to the left: Flow lines of plate motions during the last 45 Ma based on first order tectonic features. Upper panel: Paleogeography of the Late Triassic after GAETANI *et alii* (2003) on which the past plate motions have a similar undulation as today (inset of the panel to the left), indicating the persistence of the mainstream of plate motions even in the Mesozoic.

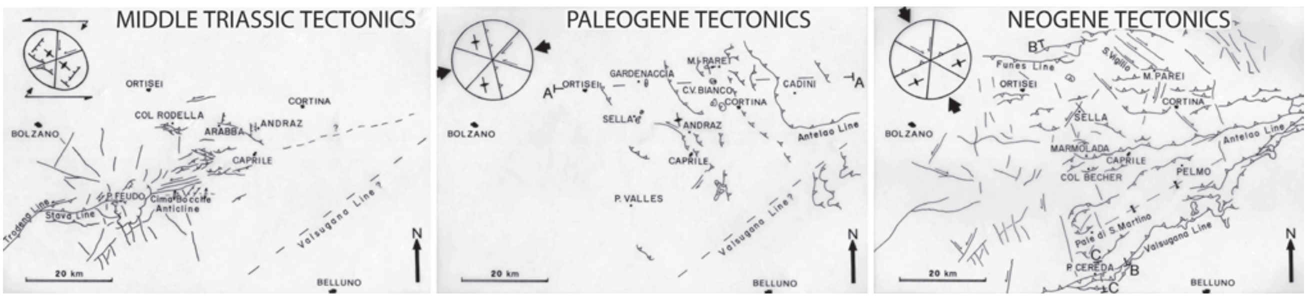


Fig. 258 - Main tectonic phases and related structures in the Dolomites after the Hercynian orogeny, apart the extensional Mesozoic tectonics (after DOGLIONI, 1987).

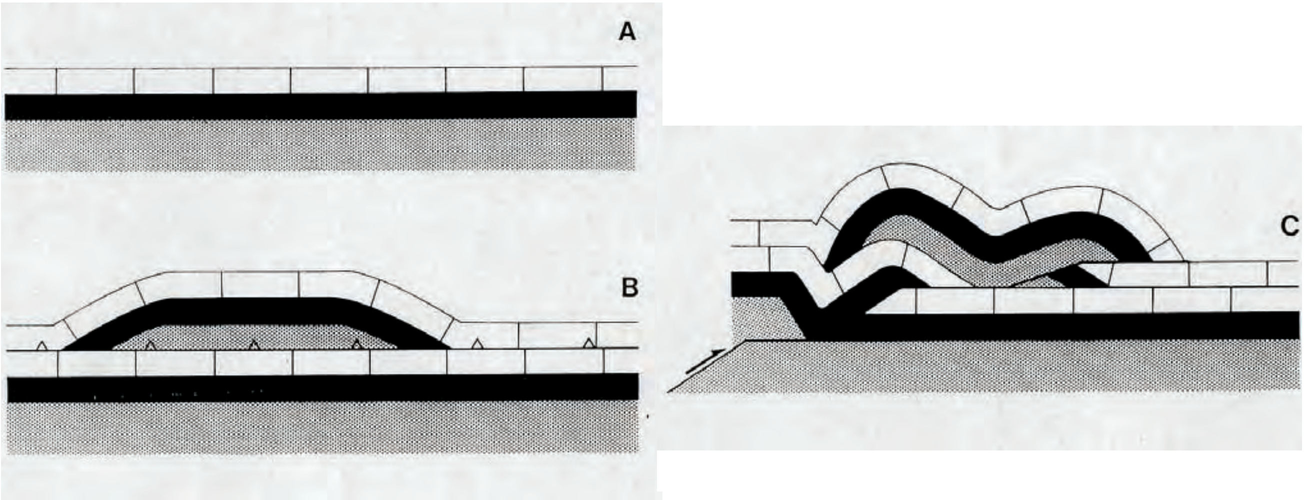


Fig. 259 - Overlap of two thrusts perpendicular to each other. A) pre-deformation stage; B) a thrust moves toward the reader with two lateral ramp cut-offs, strike view; C) later a thrust propagates with staircase trajectory, dip view. Assuming north to the left, this example could be applied to the interference pattern in the central-eastern Dolomites between older (Eocene?) WSW-verging thrusts and folds, later deformed by the deeper Miocene to Present SSE-verging thrusts and folds.

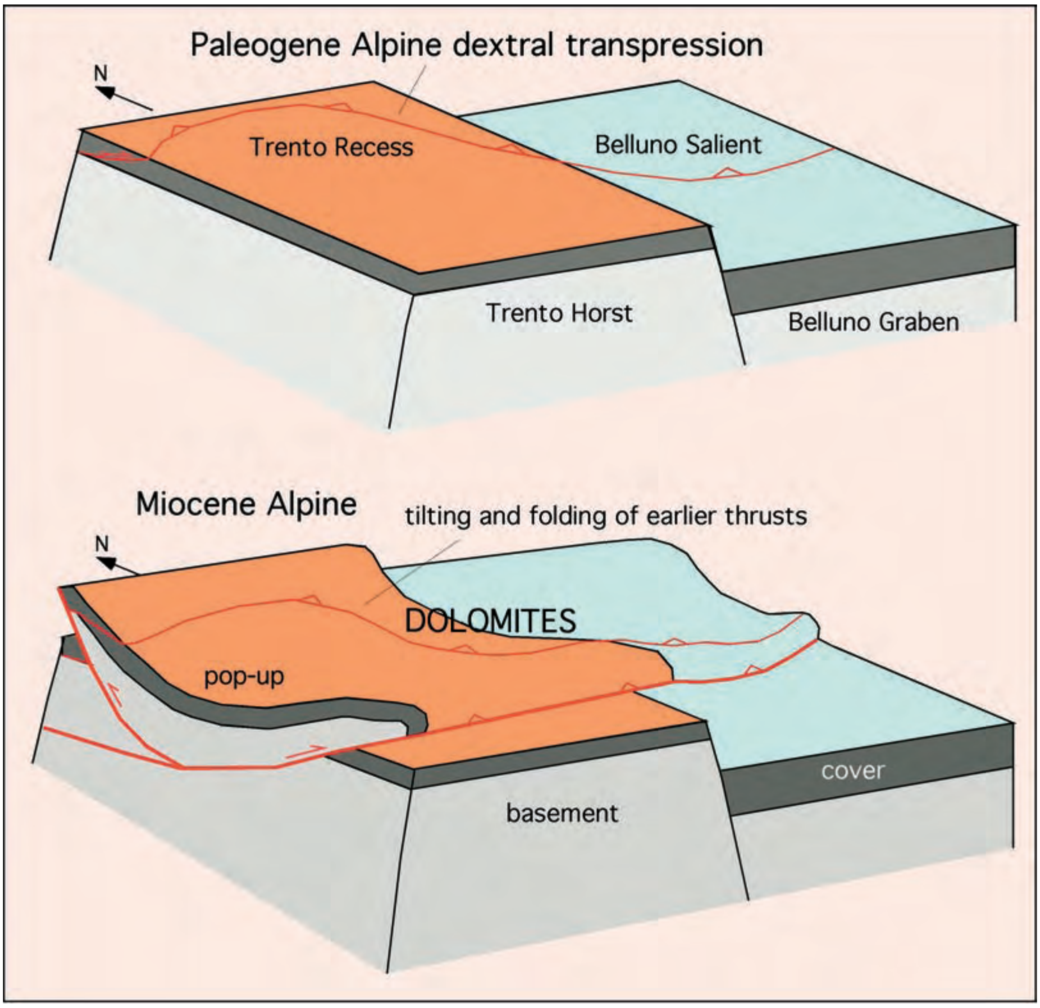


Fig. 260 - The earlier alpine deformation inherited the Trento horst determining a recess on the structural high, and a salient in the graben to the east. The transfer zone consists of right-lateral transpression with thin-skinned WSW-verging thrusts. The later deeper thick-skinned deformation, involving the basement, generated the Dolomites pop-up, folding and tilting the earlier shallower thrusts.

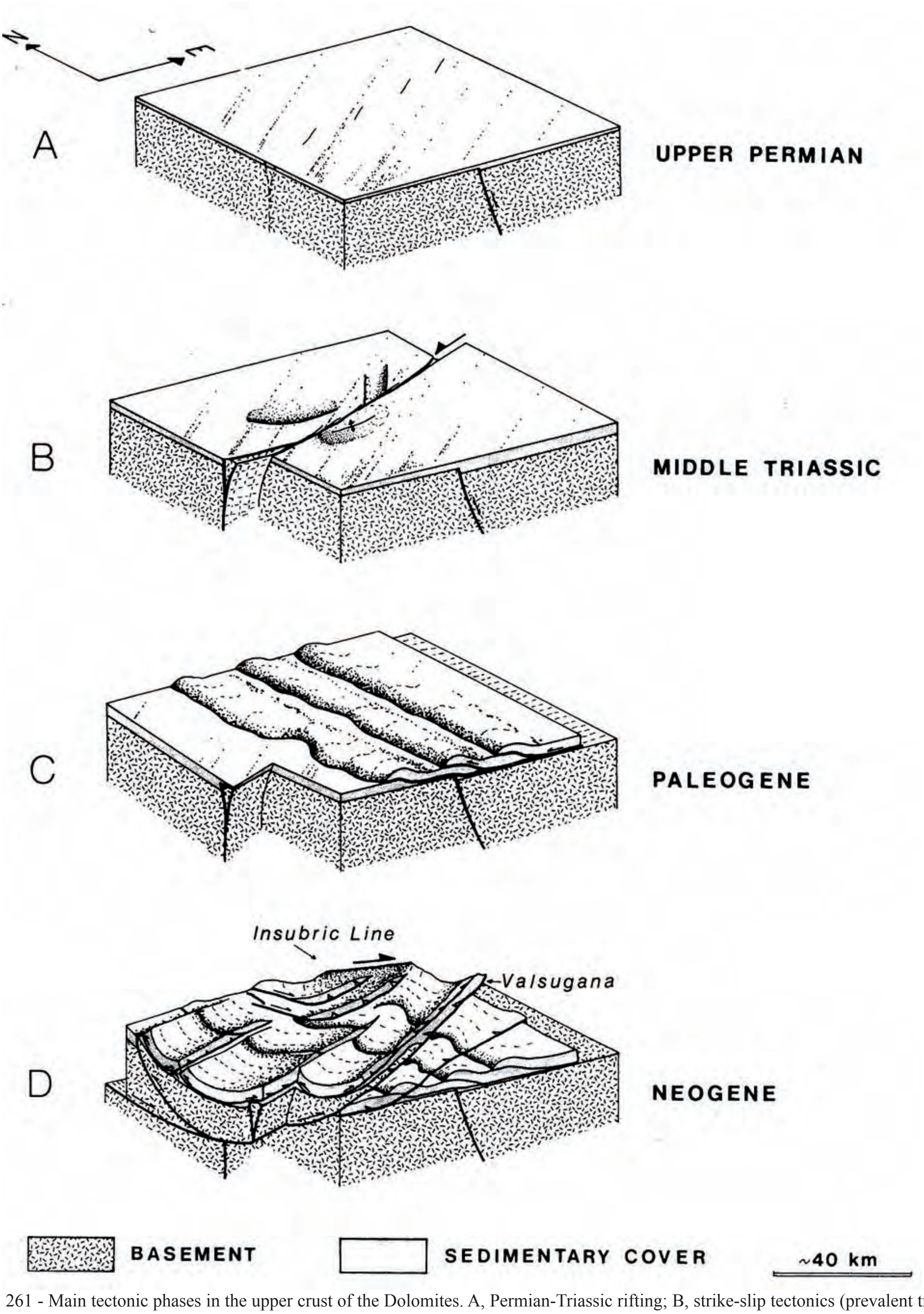


Fig. 261 - Main tectonic phases in the upper crust of the Dolomites. A, Permian-Triassic rifting; B, strike-slip tectonics (prevalent transtension with localized transpression) along a N70° trend; C, W-SW vergent thrusting of Paleogene age; D, Neogene SE-vergent thrusting, pop-up formation of the Dolomites synclinorium.

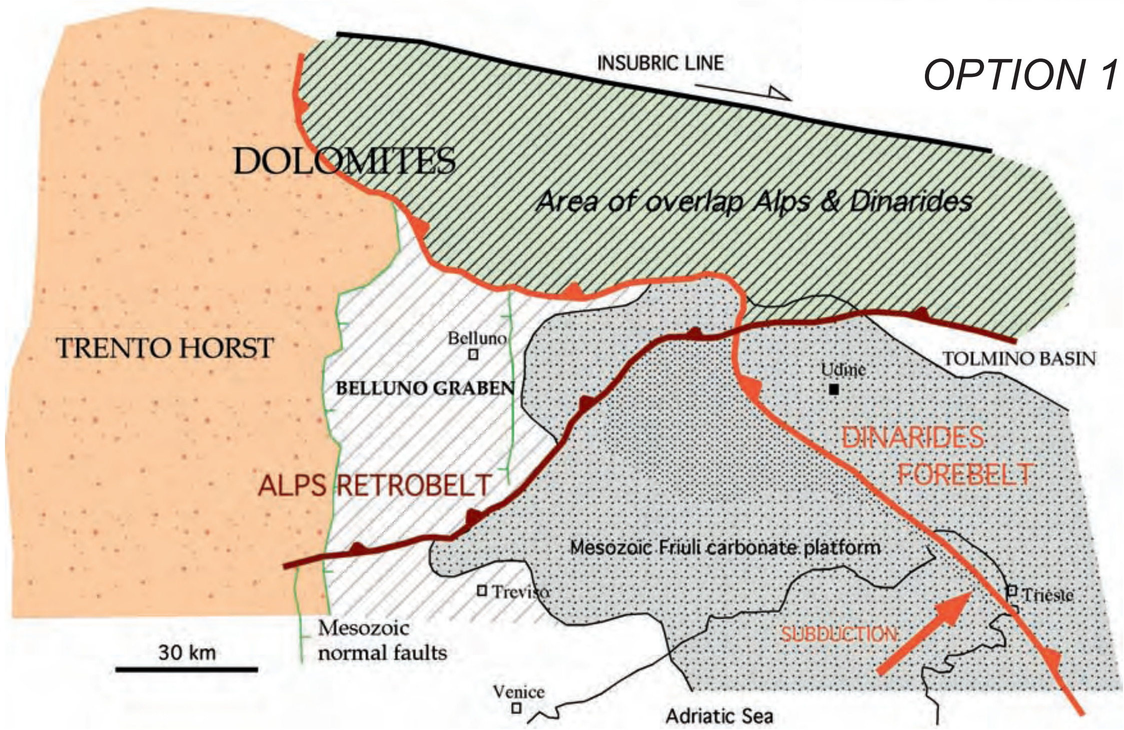


Fig. 262 - The WSW verging thrust structures of pre-Late Oligocene age in the Dolomites can be interpreted as the prolongation of the Dinarides front into the Southern Alps, in which there is a vast area of overlap and interference structures.

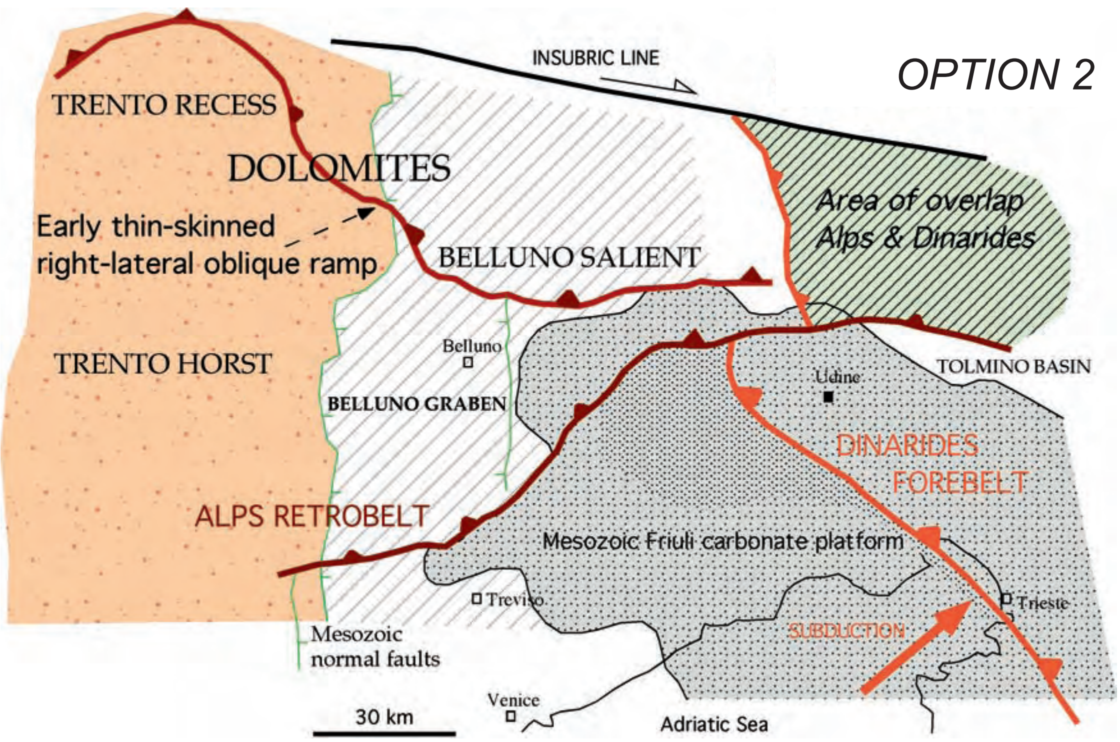


Fig. 263 - Alternatively to the previous figure, the WSW verging thrusts in the Dolomites are here interpreted as the oblique right-lateral transpressive ramp of the advancing Eocene alpine thrusting between the Trento recess and the Belluno salient. In this view the area of Alps-Dinarides overlap is more restricted to the east.

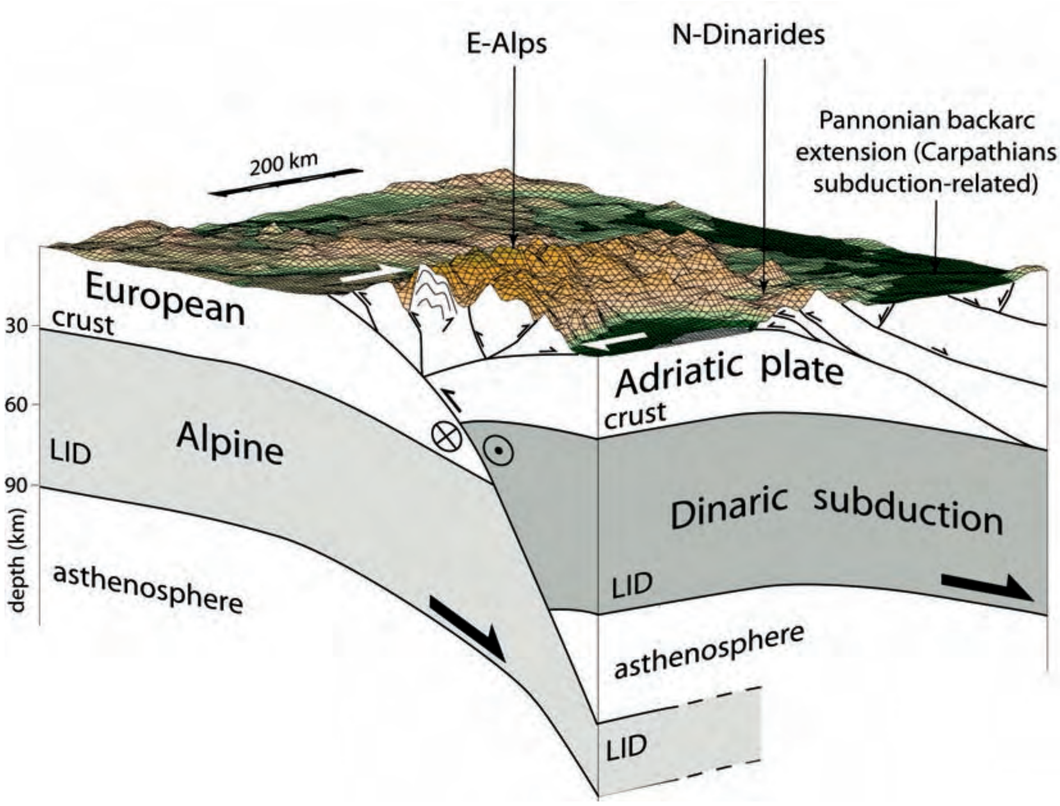


Fig. 264 - 3D view and interference between the Alpine and Dinaric subductions in northeastern Italy. The extension of the Pannonian, Carpathians subduction-related back-arc basin, crosscuts the Eastern Alps and the northern Dinarides. This indicates that, in the same area, independent geodynamic settings may concur and plate boundaries are passive features.

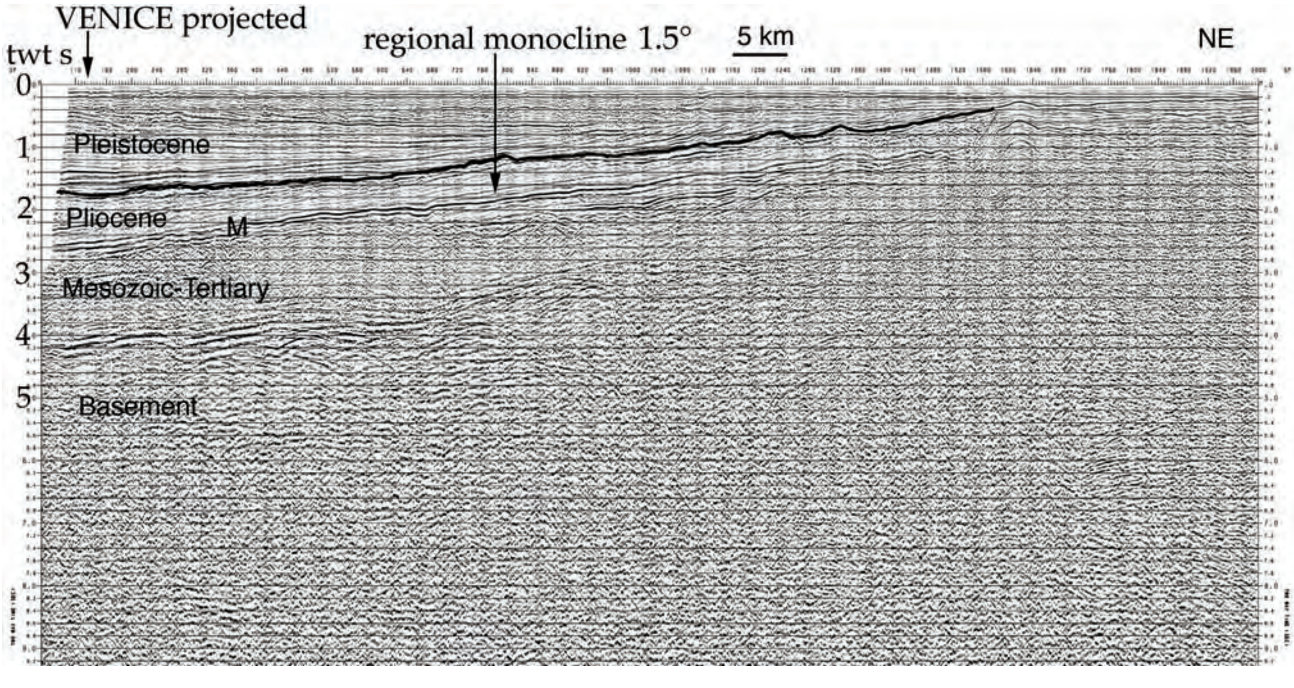


Fig. 265 - Seismic reflection profile (CROP M-18) of the northern Adriatic Sea, parallel to the coast, offshore Venice. Note the thinning of the Pleistocene sediments moving north-eastward, indicating coeval differential subsidence in the underlying rocks. The Pleistocene-Pliocene boundary is marked. M, Messinian unconformity. Vertical scale in seconds, two way time.

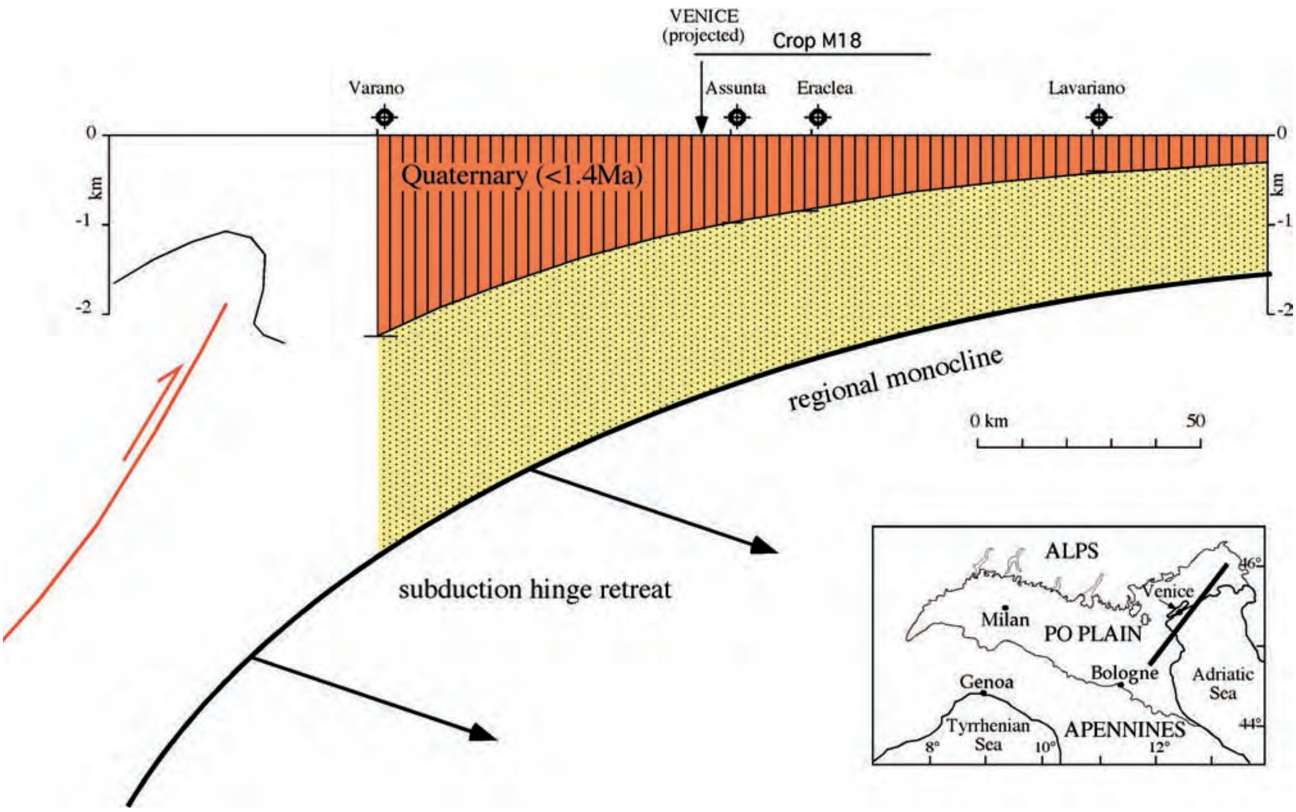


Fig. 266 - Seismic and borehole data constrain the geometry and southwestward thickening of the Pleistocene sediments in the Po Basin, northern Adriatic Sea and Friuli plain.

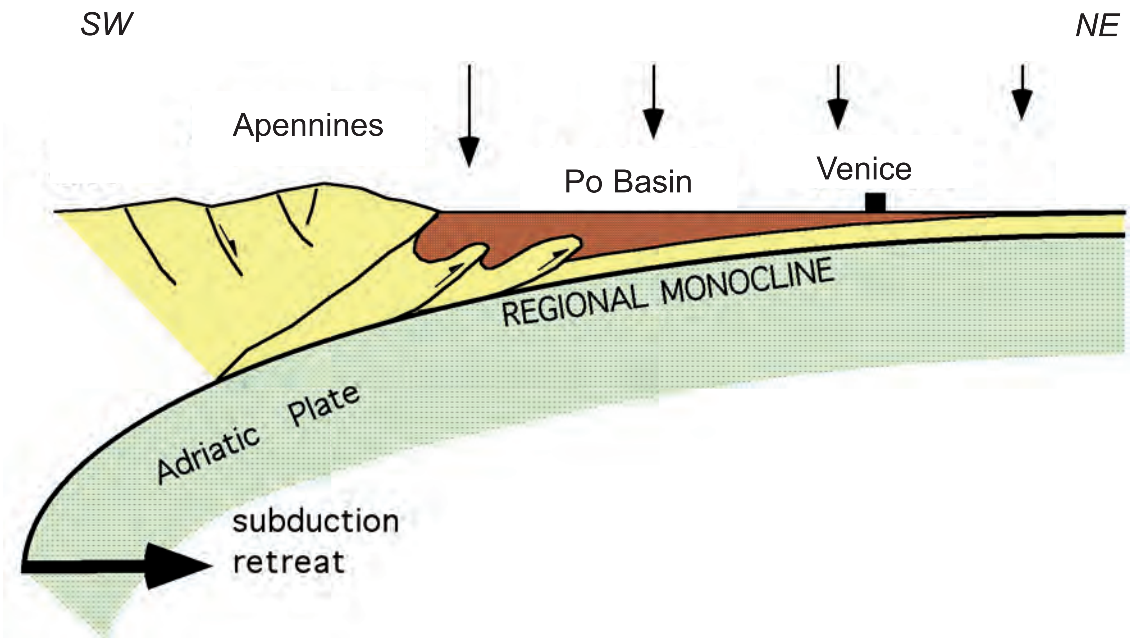
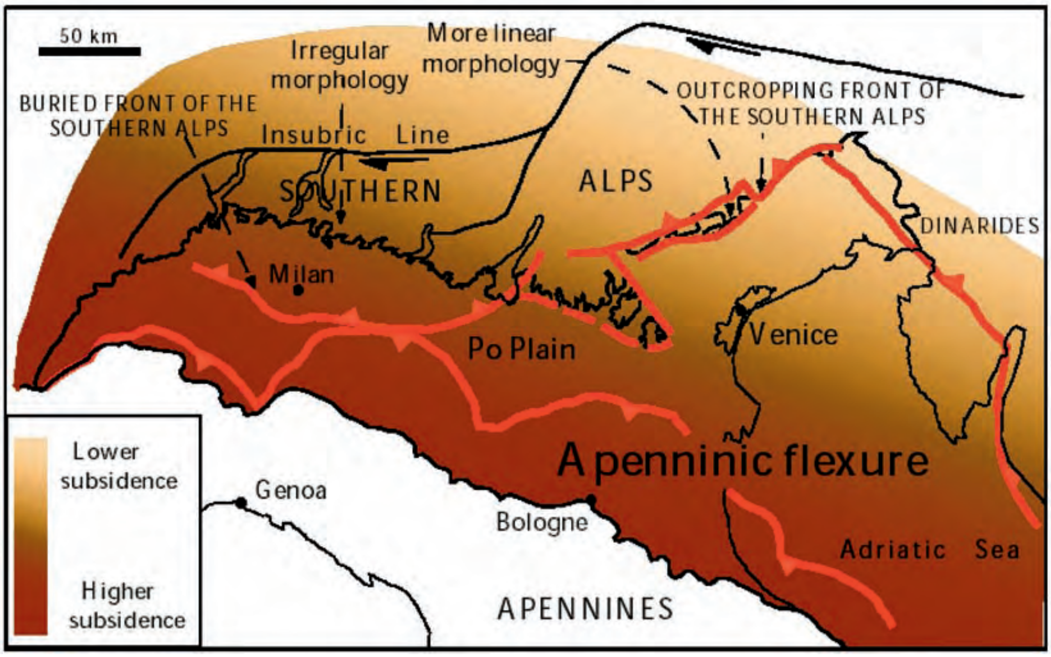


Fig. 267 - Schematic profile across the Apennines, Po Basin and Venetian area, showing the curvature of the Adriatic plate in the foreland of the Apennines, associated to the slab retreat. The 1mm/yr subsidence rate of Venice is the distal effect of the Apennines subduction hinge retreat (after CARMINATI *et alii*, 2003).



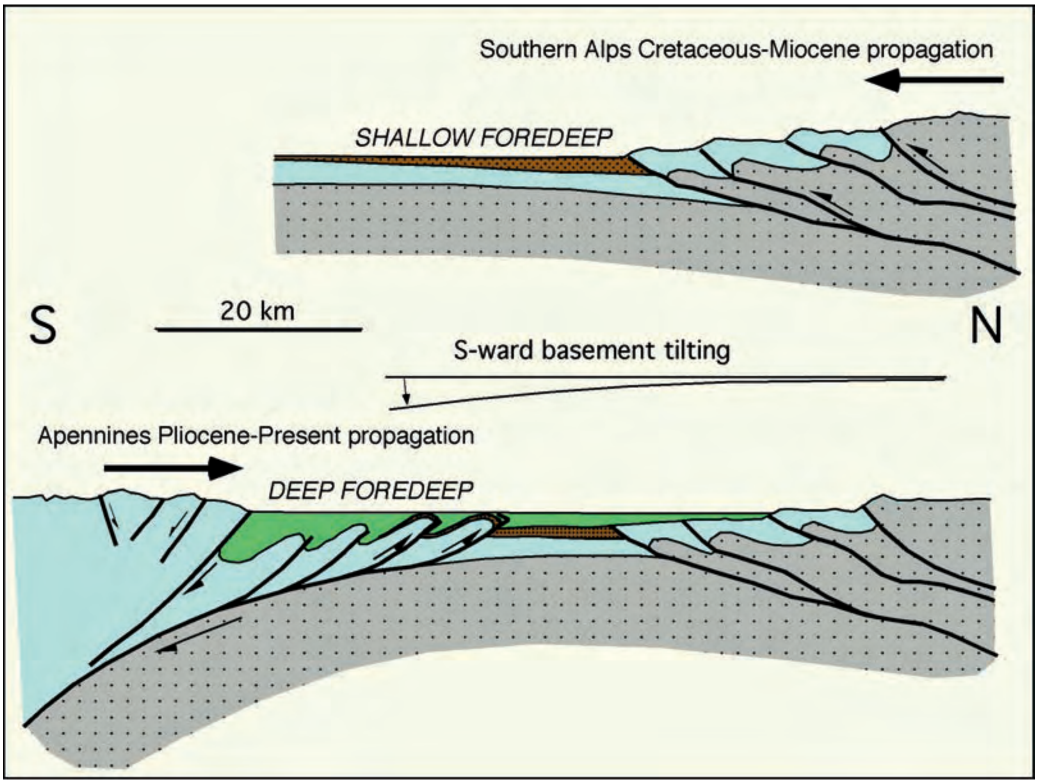


Fig. 268 - The subsidence related to the flexure induced by the Apennines subduction decreases from south to north. It affects all of the Po Plain basin and part of the Alps and of the Dinarides, where it contrasts the general uplift trend related to the orogenesis. Also the Dolomites are slightly affected by the Apennines subduction subsidence. The tectonic front of the Southern Alps corresponds to the alpine foothills in the eastern side, whereas it is buried in the western Po Basin due to the closer effect of the Apennines slab retreat. The lower panel represents an idealized cross-section between the northern Apennines and the western Southern Alps. The last ones are the south-vergent retrobelt of the right-lateral transpressive arm of the Alps, and formed between the Late Cretaceous and the Late Miocene, plus recent reactivations. Their shallow foredeep and the thrust planes have been southward tilted by the Late Miocene - Quaternary northward propagation of the basement monocline generated by the Apenninic subduction (after Doglioni, 1993; Carminati *et alii*, 2003).