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Tectonics of the Dolomites (Southern Alps, Northern Italy)

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Abstract—In post-Variscan times the Dolomites 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 transpressive event then deformed the region along a N70°E axis, generating flower structures within the basement. Volcano-tectonic domal uplift and subsequent caldera formation occurred at the same time as the Late Ladinian magmatism. Early Jurassic rifting also controlled the subsidence which increased eastward. This long period of deformation was followed by a pre-Neogene (Late Cretaceous–Palaeogene ?) E–W (ENE–WSW) compression which generated a W-vergent belt, possibly equivalent to the folded foreland of the Dinaric chain. A 70 km E–W section of the Dolomites indicates shortening of at least 10 km. During the Neogene the Dolomites, as far north as the Insubric Lineament, were the innermost part of a S-vergent 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 pre-existing thrust-planes. On the north-eastern side of the Dolomites, Neogene deformation is apparently more strictly controlled by the transpressive effects of the Insubric Lineament 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 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 Dolomites.

INTRODUCTION

THE AIM of this article is to discuss the general structural and tectonic features of the Dolomites. This is a region located in the eastern Italian Southern Alps, limited to the north by the Insubric Lineament, or Periadriatic Lineament, and to the south by the Valsugana Line (Fig. 1).

New field data and a new interpretation of the post-Variscan structural evolution of the region are presented. This region of the Alps, shown on a N–S cross-section (Fig. 2), is the innermost part of a S-verging thrust belt (Doglioni & Castellarin 1985), and records many of the events of the Alpine cycle, from the post-Variscan rifting (Winterer & Bosellini 1981) to the Alpine collision. The Dolomites may give important information about their evolution since the intensity of Alpine deformation has not been strong enough to conceal earlier tectonic events (Fig. 3).

PERMIAN AND TRIASSIC RIFTING PHASES

The Dolomites, like the whole Southern Alps, underwent rifting phases during Permian and Triassic times (Bosellini 1965a, 1973, Winterer & Bosellini 1981). Extensional tectonism, perhaps controlled by strike–slip faults, generated two major N–S trending elements of subsiding continental crust, the Atesina Platform and the Carnico-Bellunese Basin (Bosellini 1965a). In the more westerly Atesina Platform the thickness of Permian and Triassic sediments is about 2 km, whereas in the Carnico-Bellunese Basin to the east the thickness is 4–5 km (Bosellini & Doglioni 1986). Minor horsts and grabens occur within these structures (e.g. Viel 1979), breaking the upper crust into several N–S striking blocks. Permian and Triassic normal faults are not easy to recognize in the field, but different thicknesses of sedimentary cover indicate the presence of buried growth faults (Bosellini 1965b, 1968, Doglioni 1982) that do not always cut the overlying sedimentary cover. The change in thickness of the sedimentary cover across the Passo Rolle Line suggests that it is the main line separating the Atesina Platform and the Carnico-Bellunese Basin (Bosellini & Doglioni 1986).

MIDDLE-TRIASSIC TECTONICS

Local compressive tectonic features of Middle Triassic age have been demonstrated in the Dolomites (Pisa *et al.* 1979, Bosellini *et al.* 1982, Castellarin *et al.* 1982, Doglioni 1982, 1984a & b, 1985a). These structures have been interpreted (Doglioni 1984a & b) as the result of sinistral transpression with a strike of N70°E, forming the Stava and Trodena Lines, the northern limb of the Cima Bocche Anticline (Fig. 4). The basement has been strongly deformed by this sinistral transpression forming flower structures along the Stava Line–Cima Bocche Anticline which now forms a narrow and elongate basement high.

Dating of these Triassic structures (thrusts, folds and

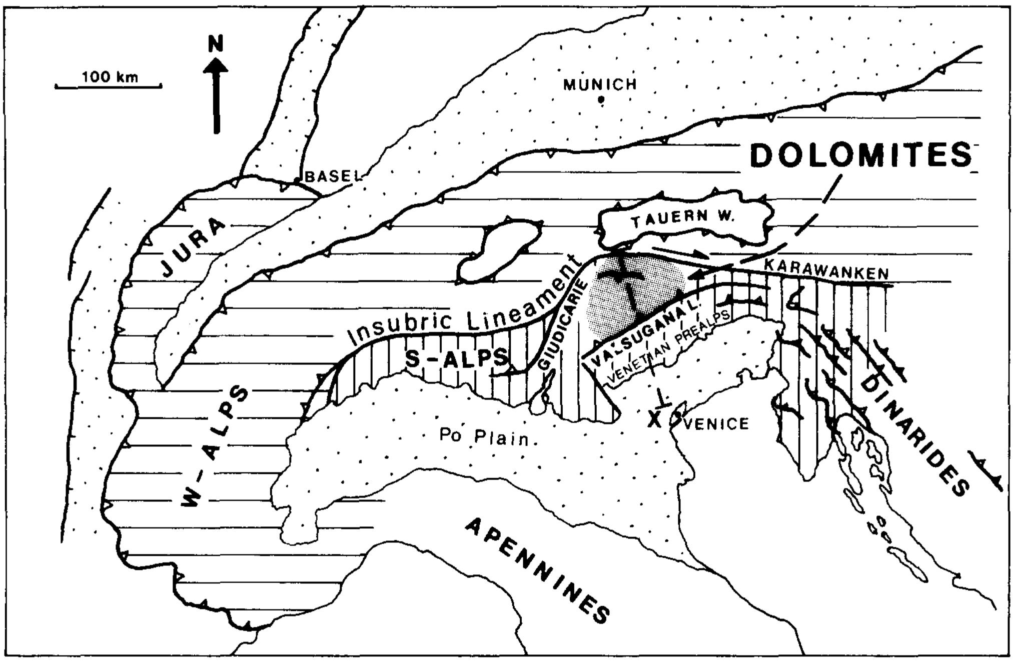

Fig. 1. Location of the Dolomites in the Alps; X shows the trace of section shown in Fig. 2.

diapiric structures) is made possible by the presence of volcanic dykes and plutonic bodies of Late Ladinian age which cross-cut pre-existing structures (Fig. 11) and by stratigraphic data from the alignment of sedimentary basins, en-échelon arrangement of normal faults controlling sedimentation and unconformable covering by volcano-clastic formations above these earlier structures. Anisian deformation is also present along the trend of the transpression, but the main sinistral strike–slip activity must have been of Late Ladinian age (Doglioni 1984a & b).

During Middle Triassic times continued differential subsidence of the basement to the east produced local basins, like the Truogolo Cadorino (Viel 1979), within the larger Carnico-Bellunese Basin. The sinistral transpression and coeval subsidence are interpreted as having been generated by the early sinistral movements between Europe and Africa (Doglioni 1984b).

VOLCANO-TECTONICS

Tectonic features of magmatic origin are also present in the Dolomites. The radial pattern of faults and of Late Ladinian volcanic dykes in the central-western part of the Dolomites (Fig. 4) suggests the presence of a domal uplift, genetically related to emplacement of Late Ladinian–Early Carnian magmatism (Doglioni 1983). Subsequent calderas and volcano-tectonic basins (Castellarin *et al.* 1982, Bosellini 1984, Blendinger 1984) complicate this structure.

JURASSIC RIFTING PHASE

The Dolomites became an internal part of a passive continental margin during Jurassic times (Bosellini 1973, Bernoulli *et al.* 1979, Winterer & Bosellini 1981), when

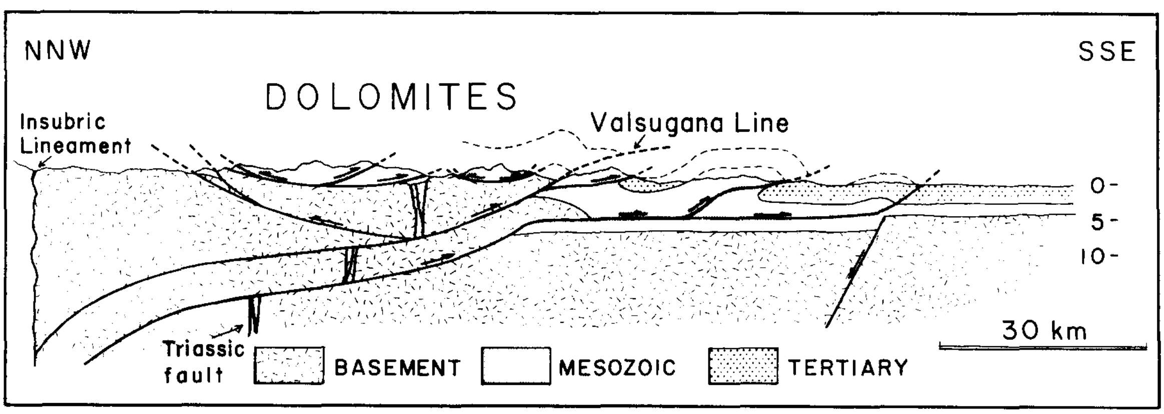

Fig. 2. Schematic cross-section of the Southern Alps across the central Dolomites, which are the innermost part of the exposed thrust belt (modified after Doglioni & Castellarin 1985). For location of the section see Fig. 1. The basement is undifferentiated; Upper Permian sediments are assumed at the base of the Mesozoic sequence and Quaternary gravels are also present on the top of the Tertiary to the south in the Veneto Plain.

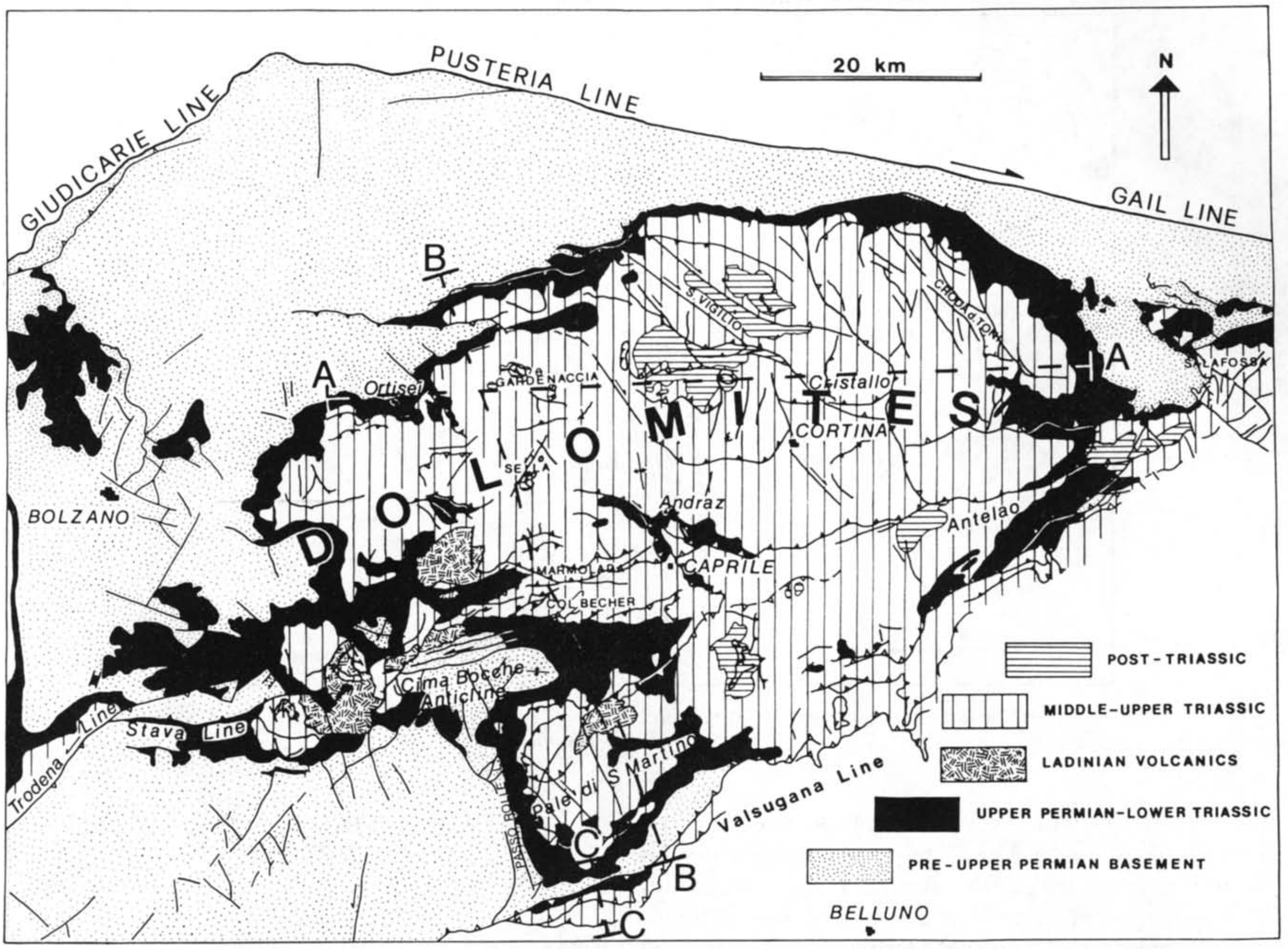

Fig. 3. General tectonic map of the Dolomites. The undifferentiated basement includes Lower Permian ignimbrites, metamorphic rocks, granitic bodies and, east of the Dolomites, the anchimetamorphic terrains of the Palaeo-Carnian Chain. A, B and C show the trace of cross-sections in Figs. 6, 8 and 9, respectively.

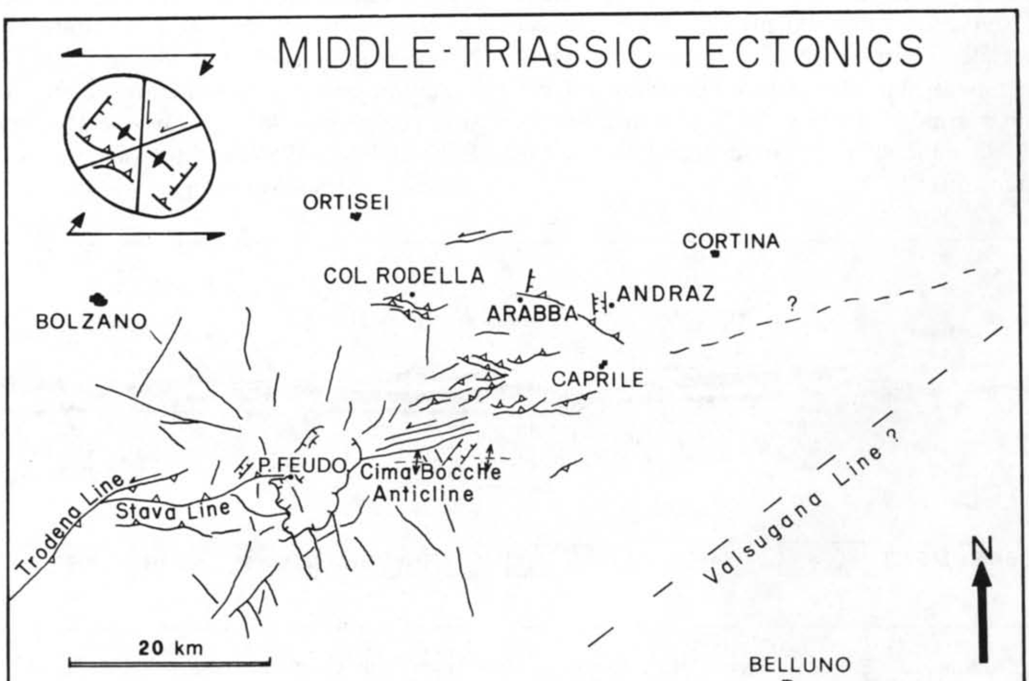

Fig. 4. Main tectonic features of Middle Triassic age in the Dolomites. Note the alignment Stava Line–northern limb of the Cima Bocche Anticline, interpreted as a sinistral transpressive zone. Volcano-tectonic features are also present in the west, related to a domal uplift and a subsequent caldera.

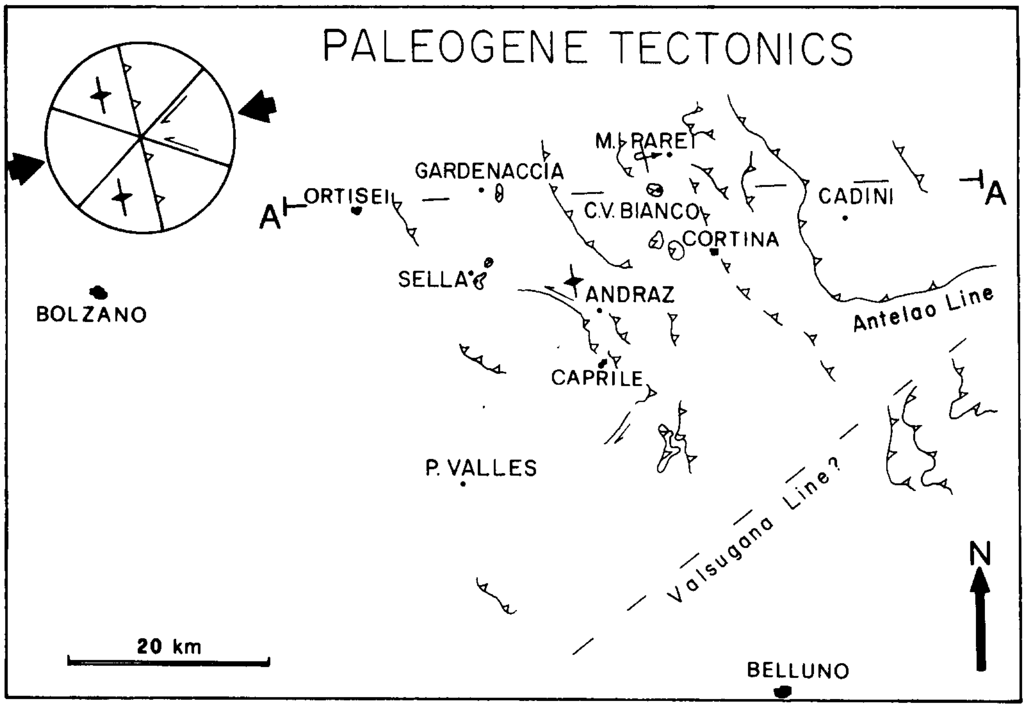

Fig. 5. Main tectonic features of pre-Neogene (Upper Cretaceous–Palaeogene?) age in the Dolomites. A–A is the trace of the section shown as Fig. 6.

the Ligurian Ocean (Western Tethys) opened to the west of the Southern Alps. This passive margin was the north-western edge of the Apulia Plate (or African promontory). Jurassic rifting continued, with differential subsidence between the Atesina Platform and the Carnico-Bellunese Basin producing a greater subsidence and related sedimentation eastwards. Tilted blocks generated angular unconformities in the Jurassic (e.g. in the Sella Group, Bosellini *et al.* 1981). A Jurassic normal fault is suspected in the Val Badia to explain the presence of a thick sequence (400–500 m) of Lower Jurassic limestones (Calcari Grigi) to the east of the valley, whilst to the west this formation is absent (Bosellini 1965b). N–S striking normal faults (e.g. S. Vigilio di Marebbe area, Salafossa mine, Fig. 3) could be related to this Jurassic extension.

PALAEO-ALPINE AND MESO-ALPINE TECTONICS

N–S or NNW–SSE trending thrusts and fold axes, W- or WSW-vergent striations on the thrust surfaces, and conjugate strike–slip faults (dextral N20°E–N60°E trending and sinistral N90°E–N120°E trending), support the presence of an E–W (ENE–WSW) compression of the region. An example of a W-vergent overthrust genetically related to this compression may be seen at Croda del Vallon Bianco (Fig. 12). This deformation involved Neocomian marls and at Monte Parei Lower Miocene conglomerates overlie structures related to this compression (Doglioni 1985a). Thus the Dolomites record an E–W or ENE–WSW compressive stress, σ_1, of Palaeo-Alpine or Meso-Alpine age (Fig. 5).

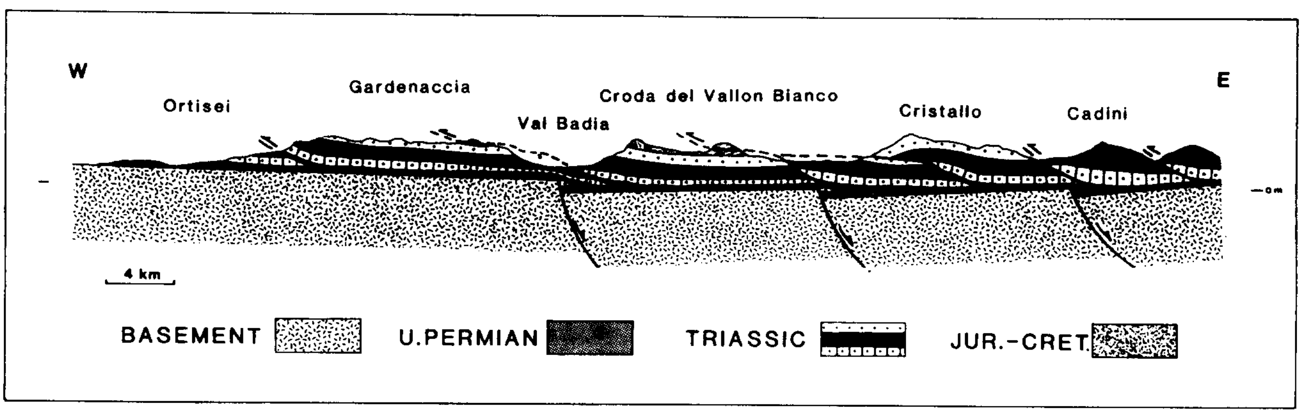

Fig. 6. Schematic E–W cross-section of the Dolomites showing the main overthrusts related to Palaeogene (?) E–W (ENE–WSW) compression. The positions of early Permo-Mesozoic normal faults in the undifferentiated basement are inferred from thickness variation of the sedimentary cover. Shortening of the sedimentary cover is at least 10 km, measured on the basis of the minimum displacement of thrusts. Structurally this section looks like a folded foreland and may be the westernmost external part of the Dinaric chain. Neogene structures are not shown in this diagram. For location of the section see Figs. 3 and 5.

From an E–W schematic cross-section (Fig. 6), these W-vergent (or more exactly WSW-vergent) thrusts appear thin-skinned with detachment horizons in the evaporitic Upper Permian Bellerophon Formation, the evaporitic horizons of the Scythian Werfen Formation, the Anisian Lusnizza Formation, and in the Carnian Raibl Formation to the east. This E–W (or ENE–WSW) compression may have reactivated N–S block-faults of Permian or Mesozoic age since the thickness of the sedimentary cover increases eastwards, sometimes suddenly, in the cross-section of Fig. 6. The location of these normal faults cutting the basement is hypothetical, due to lack of seismic information.

On a larger scale, these N–S stuctures are most likely to be related to the Palaeogene Dinaric chain (Fig. 1), and could be the westernmost external deformation of this belt. The cross-section (Fig. 6) is about 70 km wide and suggests a shortening of the sedimentary cover by at least 10–11 km (from a line length restoration). The shortening within the basement could have been greater to the east, on the inner part of the Dinaric chain.

However, in the Karawanken region, the dextral Neogene Insubric Lineament (Gail segment) probably cuts the connection with the 'root zone' of these W-vergent structures of the Dolomites (Fig. 1). Most of the 'Summit Overthrusts or Gipfelfaltungen' (isolated klippen of Norian and Jurassic carbonates now observable at the top of many Dolomitic mountains, Furlani 1909, Reithofer 1928, Castiglioni 1931, Accordi 1955, Leonardi 1955, 1965a & b, Colacicchi 1960, Doglioni 1985a) have been generated by post-Early Cretaceous, pre-Neogene, E–W compression (Doglioni 1985a). Palaeogene flysch of eastern provenance, preserved just to the south of the Dolomites, may be related to the emerging Dinaric chain (Massari personal communication). Therefore the pre-Neogene Alpine tectonics of the Dolomites may be related to this geodynamic event.

In the Bergamasc Alps (Gaetani & Jadoul 1979), to the west of the Dolomites, a Palaeo-Alpine or Meso-Alpine phase of N–S compression produced folds and thrusts with N70°–90°E strike, pre-dating the *ca* 40 m.y. Adamello intrusion (Brack 1981). However, such structures have yet to be recognized in the Dolomites, where Late Cretaceous and Palaeogene sediments are lacking, but it is possible that these old Alpine structures continued in a transpressive way within the Giudicarie Belt, without involving the Dolomites.

N–S striking volcanic dykes of Late Cretaceous–Early Tertiary age have also been recognized in the Dolomites (Lucchini *et al.* 1983), which suggest extension phases during these times.

NEOGENE TECTONICS

In a N–S section (Fig. 2), the central Dolomites form a wide synclinorium, genetically related to the Valsugana Overthrust in the south and its N-verging backthrusts to the north (Funes and Passo delle Erbe Lines, Figs. 7 and 8). The Dolomites, thus, form a piggy-back thrust terrain with two complementary overthrusts (S- and N-verging, Fig. 8) displacing basement in a pop-up geometry (e.g. Butler 1982).

The Valsugana Line thrusts Miocene sediments (Venzo 1940) and Lower Miocene sediments at Monte Parei (Cros 1978) are cut by a later thrust. However, the age of the N-vergent backthrusts in the northern part of the Dolomites is uncertain. The strike of Neogene thrusts and folds ranges from N90°E to N50°–60°E, but it

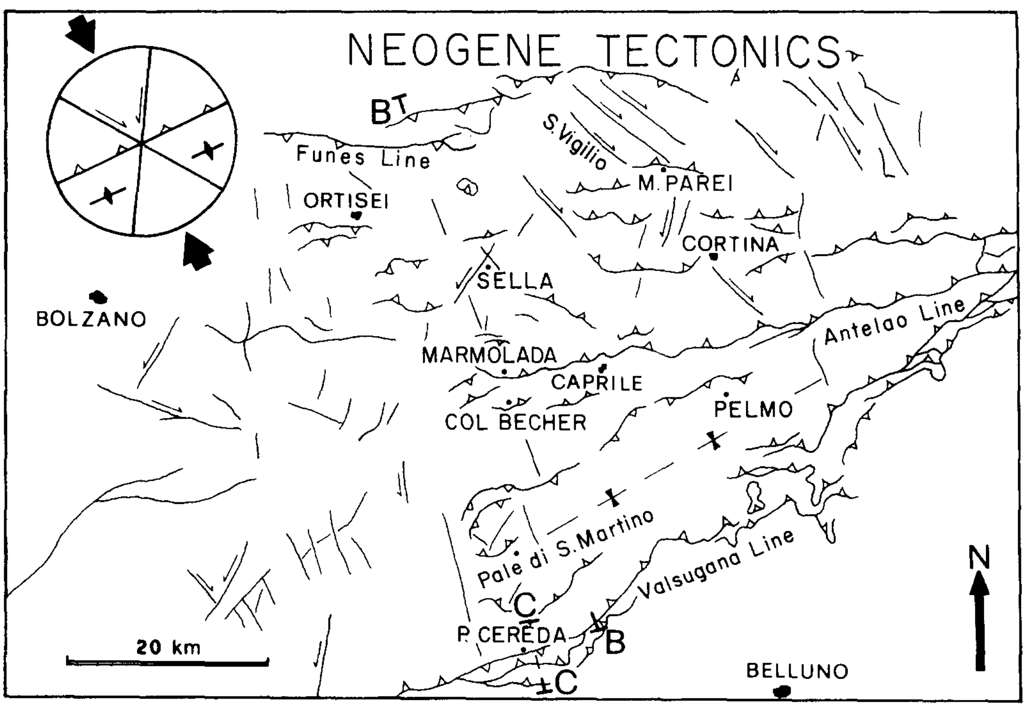

Fig. 7. Main tectonic features of Neogene age in the Dolomites. B–B and C–C are the traces of the sections shown as Figs. 8 and 9.

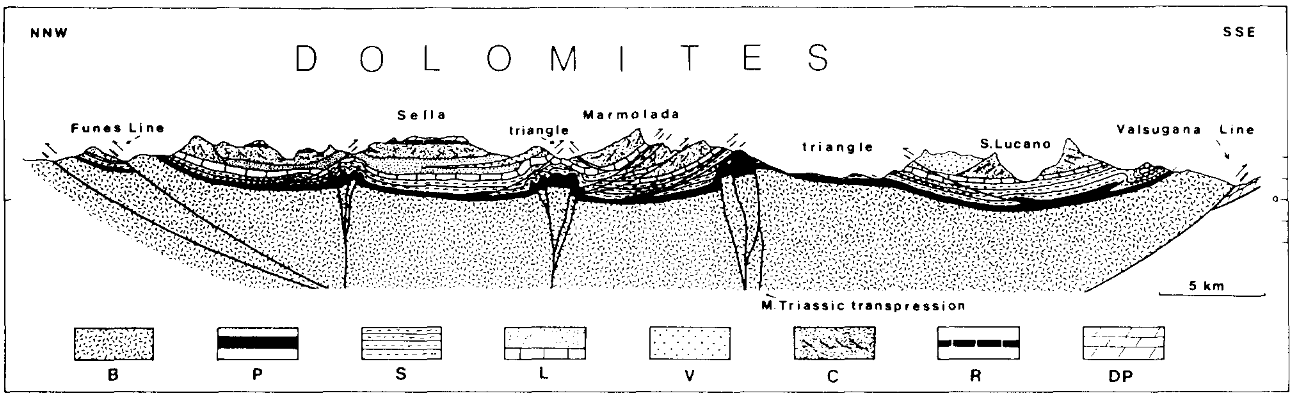

Fig. 8. N–S cross-section of the central Dolomites. The wide synclinorium or pop-up, is generated by the Valsugana Overthrust in the south, and by backthrusts on the northern side (i.e. Funes Line). Deformation in the basement is mainly inherited from Middle Triassic transpressive structures: note also Triassic diapiric squeezing above the transpression. The sedimentary cover adapted itself to the synclines of the underlying basement mainly by flexural slip. Triangle zones are present above the inherited structural highs. Pre-Neogene (Triassic and Palaeogene) overthrusts are oblique to the section and complicate the structure (e.g. Marmolada). For this reason the section is not retrodeformable in the central part. For location of the section see Figs. 3 and 7. Legend: B, undifferentiated pre-Upper Permian basement; P, Upper Permian (Val Gardena Sandstones and evaporitic Bellerophon Formation, seat of detachments); S, Scythian Werfen Formation; L, Anisian (Contrin Formation) and Ladinian-Carnian basinal sequences (Livinallongo Formation, Wengen Formation, S. Cassiano Formation); C, Ladinian and Carnian carbonate platforms; R, Upper Carnian Raibl Beds; DP, Norian Dolomia Principale.

is unclear if this variation is a consequence of two different tectonic phases. Conjugate strike–slip faults trend N30°–60°W (dextral displacement) and N0°–30°E (sinistral displacement). Several valleys in the central and northern Dolomites now lie along dextral strike–slip faults (e.g. Valparola, Valle di S. Vigilio, Fig. 7). These strike–slip faults often show both positive and negative flower geometries (*sensu* Harding 1985), as at Croda de Toni. From the orientation of thrusts, fold axes, striations on thrust surfaces, and the directions of the conjugate strike–slip faults, the Neogene σ_1 would be about N30°W (Fig. 7).

Neogene deformation generated most of the present elevation of the Dolomites, which form a slab of upper crust carried southwards by the Valsugana Overthrust. The central Dolomites form the innermost part of the Neogene thrust-belt of the Southern Alps (Fig. 2). To the south (i.e. south of the Valsugana Line) the sedimentary cover of the Venetian Prealps is considerably shortened. In the central Dolomites, the sedimentary cover has generally been preserved (Fig. 2), and the basement has been displaced southwards by the Valsugana Line for at least 8–10 km (Bosellini & Doglioni 1986), uplifting the Dolomites by 3–5 km. Along the Valsugana Overthrust very complicated structures are developed (e.g. Semenza 1959); for example the basement wedge within the sedimentary cover forms 'fish structures' (Fig. 9), and generated a substitution of cover as described in the Orobic Alps (Laubscher 1985).

The basement synclinorium, associated with the Valsugana Line and its backthrusts to the north, produced folding of the overlying sedimentary cover (Fig. 8). The flower structures inherited from Triassic times have complicated the core of the synclinorium. The sedimentary cover adapted itself to Neogene folding of the basement by generating 'semi-cylindrically' shape folds (Fig. 8), by flexural slip or flexural flow. These folds trend N50°–80°E, the largest of which crops out between the hangingwall of the Valsugana Line and the Triassic structural high (flower structure) in the core of the synclinorium from Pale di S. Martino and Pale di S. Lucano eastwards to Pelmo–Antelao (Figs. 3, 7 and 8). The main décollements are located in the Upper Permian evaporites of the Bellerophon Formation and within incompetent units at higher stratigraphic levels. Within or between these décollements, local triangle zones are defined by convergent thrusts, as to the east of Cortina (Figs. 3 and 7) and to the north of the Pale di S. Lucano (Fig. 8).

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 (Fig. 8) without taking into account inherited pre-Neogene structures.

On the north-eastern side of the Dolomites the Valsugana Line is closer to the transpressive effects of the Insubric fault (Pusteria and Gail segments, Fig. 3), hence the synclinorium is narrow. Several thrusts show a dextral en-échelon arrangement with respect to the Insubric Lineament. The shortening could be greater than that in the central Dolomites and 3-dimensional balanced sections are necessary to restore the W-vergent thrusts.

Finally, in the western Dolomites, structures show a NNE–SSW trend, parallel to the Giudicarie Line. Thus, the Giudicarie belt probably slightly deformed the western side of the Dolomites; this deformation could be confused with pre-Neogene structures of the central-eastern Dolomites, which trend N–S to NNW–SSE.

It is unclear if gravity gliding occurred in the limbs of

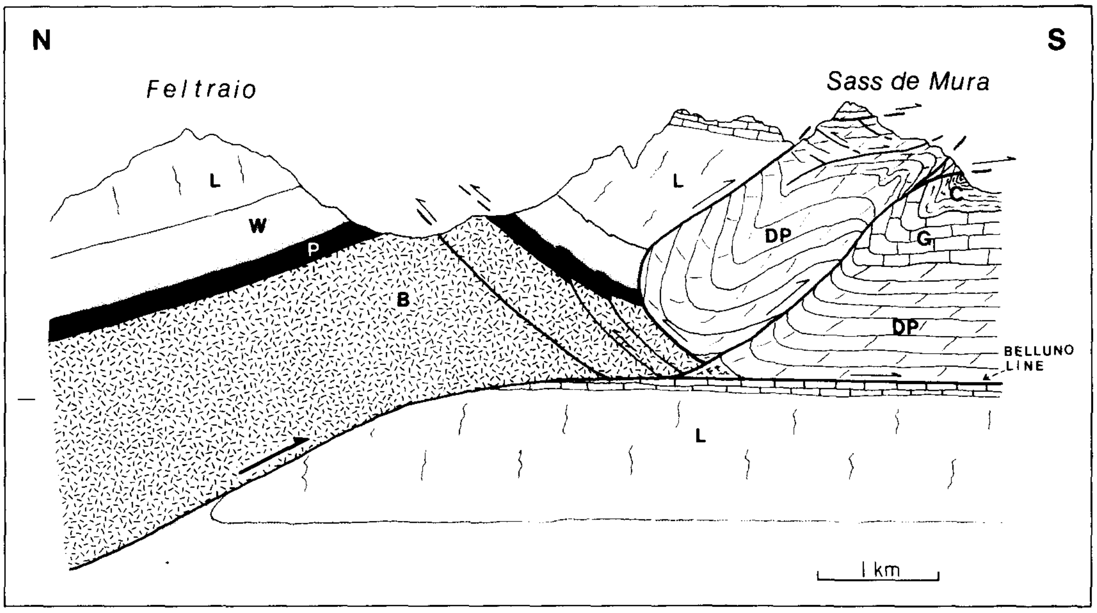

Fig. 9. Cross-section along the Valsugana Line, at the southern margin of the Dolomites in the Passo Cereda area. The basement (B) of the Dolomites overthrusts and wedges into the sedimentary cover of the Prealps in the south forming a 'fish structure'. The basement shows a ramp fold geometry. The southern limb of the fold shows the dragged Dolomia Principale (DP) wedged between basement and Ladinian carbonates (L) generating another N-vergent 'fish structure', with substitution of the cover at its base (contact basement—Dolomia Principale). This kind of structure could be present along the Valsugana Line in the whole Agordo Cereda area. Note that displacement of the main basement thrust must be absorbed by the branch line (Belluno Line) to balance the section. For location of the section see Figs. 3 and 7. Schematic stratigraphy: B, undifferentiated basement; P: Upper Permian sediments; W, Scythian and Anisian formations; L, Ladinian carbonates; DP, Dolomia Principale; G, Jurassic limestone; C, Cretaceous limestone and marls.

the wide synclinorium of the central Dolomites; but N- and S-vergent detachments in the basal levels of the sedimentary cover, on its northern and southern limbs respectively, do not support this hypothesis.

A last poorly supported hypothesis is that N–S compression, with little detachment of the sedimentary cover, could be of pre-synclinorium age, with the 'root zone' in the Alps s.s., later disconnected and refolded by transpression along the Insubric Lineament.

INHERITED TECTONIC STRUCTURES IN DOLOMITES

From the preceding text it is clear that the Dolomites record several tectonic phases, from Permian rifting to Neogene compression. Each tectonic phase inherited the pre-existing structures of earlier phases. We can see a clear example of this in the Caprile-Digonera area where a Palaeogene (?) W-vergent overthrust has been faulted and folded by a later S-vergent Neogene overthrust, resulting in a complicated polyphase structure (Fig. 10). The Antelao Line in the eastern Dolomites also shows a W-vergent geometry later refolded by a northward dipping thrust. At Andraz, a small Anisian graben with N–S strike experienced E–W compression probably of Palaeogene age (Figs. 13 and 14). At Col Becher, an overthrust which is of Middle Triassic age has been folded and reactivated probably during Neogene tectonics. At Col Rodella, overthrusts of Upper Ladinian age (Pisa *et al.* 1979) have been reactivated and are sometimes observed folded by the later Alpine tectonism.

Alpine overthrusts have also been controlled by earlier Triassic flower structures: for example the position of the triangle zones in Fig. 8 is above old structures, and the Triassic structural highs influenced the strike of the W-vergent overthrusts (Fig. 19). The largest of these structural highs, the Stava Line–Cima Bocche Anticline, acted as an obstacle to Neogene folding of the sedimentary cover during the formation of the synclinorium of the Dolomites (Fig. 8).

The radial pattern of normal faults related to volcano-tectonic domal uplift has been partially reactivated by Neogene strike–slip faults (Figs. 4 and 7). Jurassic, eastwards dipping, listric normal faults may have been reactivated as W-vergent thrust planes during Palaeogene compression. Similarly W-vergent thrust planes may have been reactivated as S-vergent thrusts during Neogene tectonics.

Striations on strike–slip faults often show both dextral and sinistral displacements indicating reactivation. For example, Palaeogene dextral N30°E faults may have been reactivated as sinistral Neogene faults, and sinistral N110°E faults as dextral Neogene faults. One of the best examples of inherited geometry is exposed in the hangingwall of the Valsugana Line where pre-existing Permo-Mesozoic horst and graben are oblique to Neogene thrusting and have been displaced southwards (Fig. 19). The Atesina Platform in the western Dolomites and the Carnico-Bellunese Basin to the east may in fact be seen in the hangingwall of the Valsugana Line (Bosellini & Doglioni 1986). In the western Dolomites

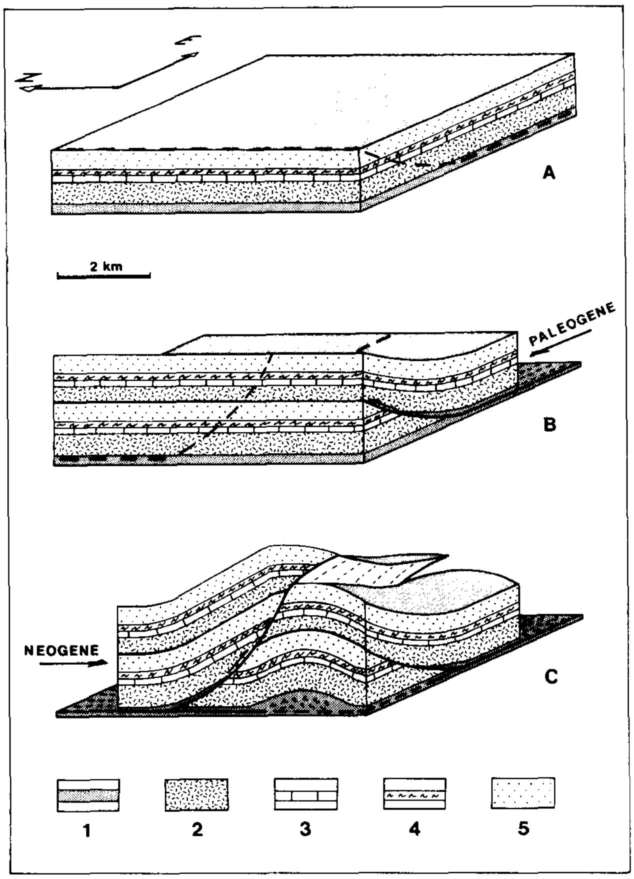

Fig. 10. Block-diagram of the superposition of two Alpine tectonic phases in the Caprile-Digonera area: a W-vergent Palaeogene (?) overthrust has been faulted and folded by a later S-vergent Neogene overthrust. A, pre-deformation situation; B, E–W compression; C, N–S compression. Legend: 1, Upper Permian evaporitic Bellerophon Formation; 2, Scythian Werfen Formation; 3, Upper Anisian Contrin Formation; 4, Ladinian Livinallongo Formation; 5, Upper Ladinian–Lower Carnian volcano-clastic sediments.

the Alpine Giudicarie belt has sinistrally bent the Triassic transpressive N70°E alignment (Doglioni 1984b).

SEDIMENTARY CONTROLLED STRUCTURES IN THE DOLOMITES

Sedimentary geometry has also strongly conditioned the tectonics. Slopes of Ladinian and Carnian carbonate platforms are commonly the locus of ramps for overthrusts of Triassic, Palaeogene or Neogene age (Doglioni 1985a). Rigid carbonate bodies behave very differently to evaporitic or marly sequences. Hence the Dolomites often show a much stronger deformation in the more incompetent sediments around the Triassic carbonate platforms.

The staircase trajectory of the overthrusts is connected with marked differences in the rheological behaviour of the different stratigraphic horizons. Evaporitic and incompetent layers (Bellerophon Formation, Werfen Formation, Raibl Formation) have acted as major décollements (flats) during overthrusts and folding of the sedimentary cover (Fig. 8).

In the Sella Group, some synsedimentary differential subsidence between the margin of a Carnian carbonate platform (Cassian Dolomite) and its core is related to differential compaction of incompetent basinal sediments (S. Cassiano Formation), which are thicker beneath the margin of the platform. This differential subsidence conditioned the subsequent deposition of the Raibl beds, which are thicker above the margin of the platform than in the core.

GENERAL TECTONICS

The different tectonic phases of the Dolomites formed mainly at low temperatures (diagenesis) and are essentially brittle tectonics (Figs. 15 and 16). However, Ladinian magmatism, Mesozoic burial and the Alpine event produced anchimetamorphic temperatures. Slow ductile behaviour has been recognized for the Werfen Formation (Doglioni 1985b), and a temperature of about 200°C, suggestive of anchimetamorphism conditions (Garzanti 1985), has been proposed for Carnian sandstones in the western part of the Southern Alps.

Evaporites in the basal Upper Permian Bellerophon Formation (Fiammazza facies) clearly show ductile deformation (Fig. 17); but this need not imply high temperatures. The deformation of the Bellerophon Formation is related to development of the main décollement horizons, and contains folds with an axial-planar cleavage and thickened hinges (Fig. 17). Along the Middle Triassic N70°E alignment, the Bellerophon For-

Fig. 11. Example of Ladinian pre-volcanic deformation: a Ladinian volcanic dyke (V) cross-cuts chevron folds in Upper Anisian limestone (A) at Passo Feudo. This deformation is preserved along the Middle Triassic transpressive lineament, the Stava Line-Cima Bocche Anticline.

Fig. 12. Example of Palaeogene E–W compression at Croda del Vallon Bianco. The W-vergent overthrust is viewed northwards from the top of Tofana III (see Fig. 6). Note the ramp of the thrust on the right within the Jurassic limestone (J), and the flat at the base of the Lower Cretaceous marls (C). Note also the horses enclosed by two minor duplexes along the thrust plane. Drag folds are present especially in the ramp, both in the hangingwall and in the footwall. Kink-bands may also be seen in the footwall.

Fig. 13. Examples of superposition of two tectonic phases at Andraz, Dolomites: a small Anisian graben with N–S strike has been refolded by the E–W pre-Neogene compression; note the folds inside. S, Siusi Member of the Werfen Formation; G, Gastropod Oolite of the Werfen Formation, stratigraphically overlying the Siusi Member. The little circle indicates the location of the detail shown as Fig. 14.

Fig. 14. Detail from Fig. 13 showing folding of bedding and recompression of small normal fault within the graben; Gastropod Oolite of the Werfen Formation, Andraz, Dolomites.


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V
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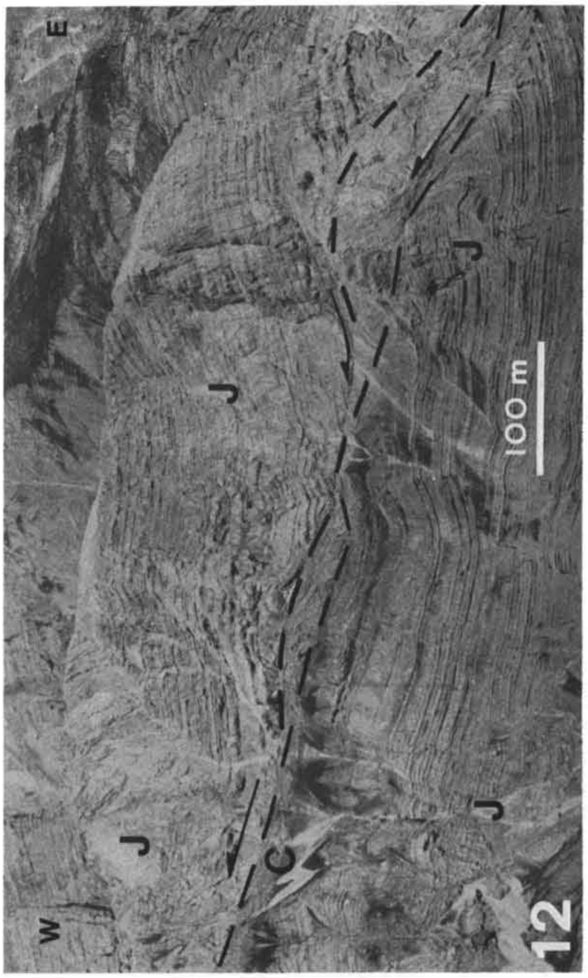
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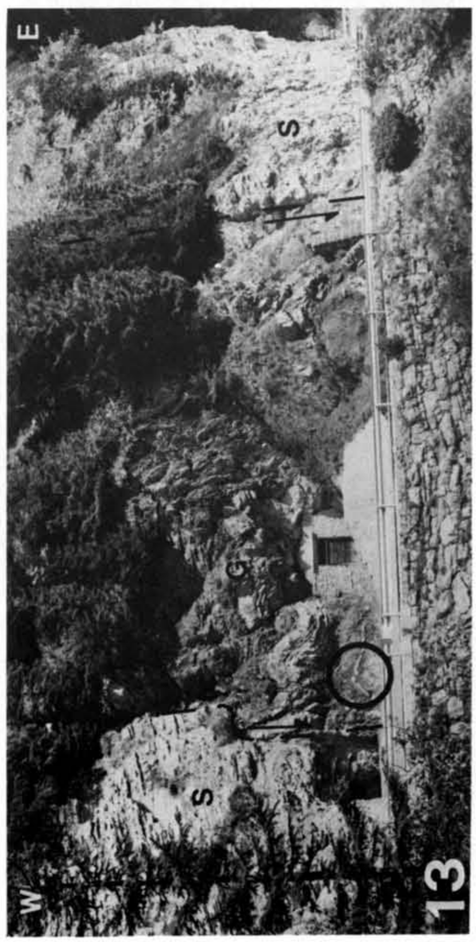
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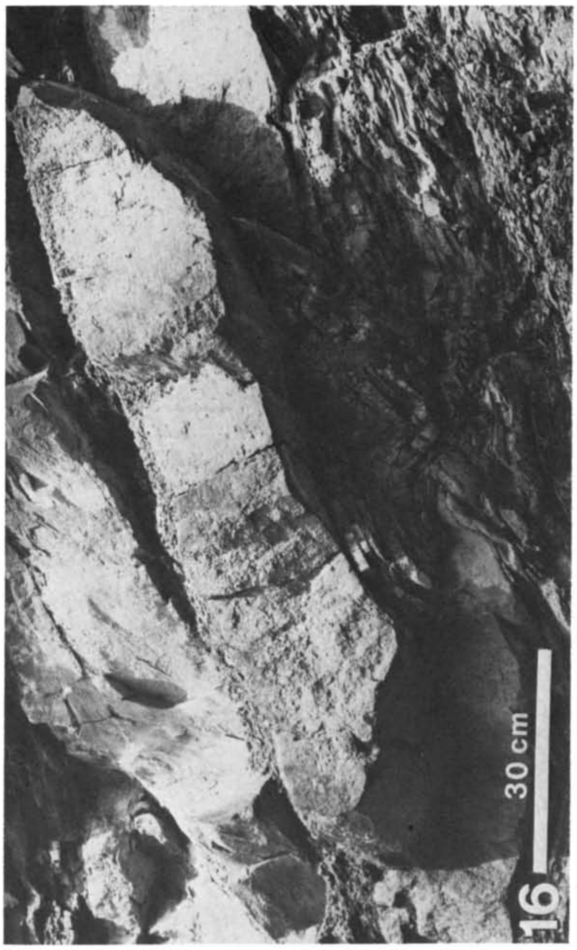
16
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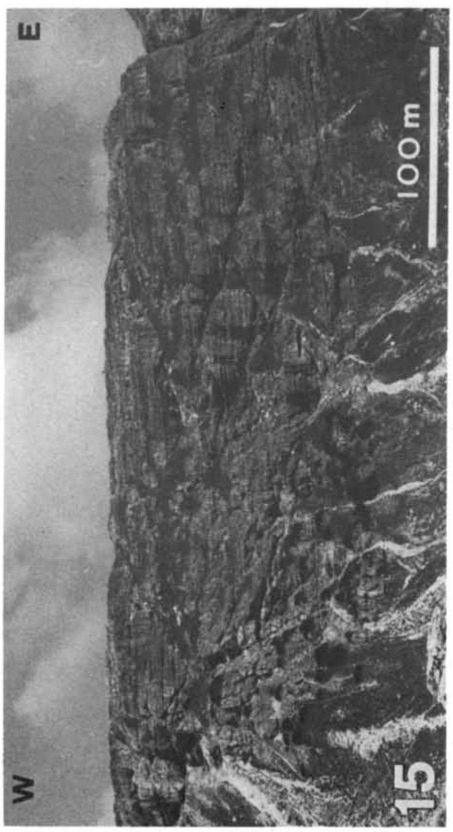
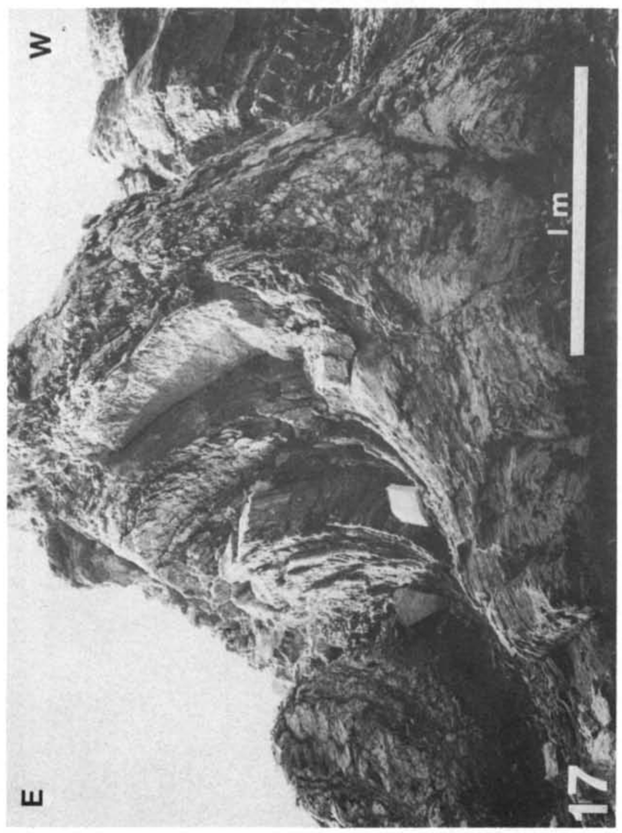
10m


W
E
15
100 m


E
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1 m

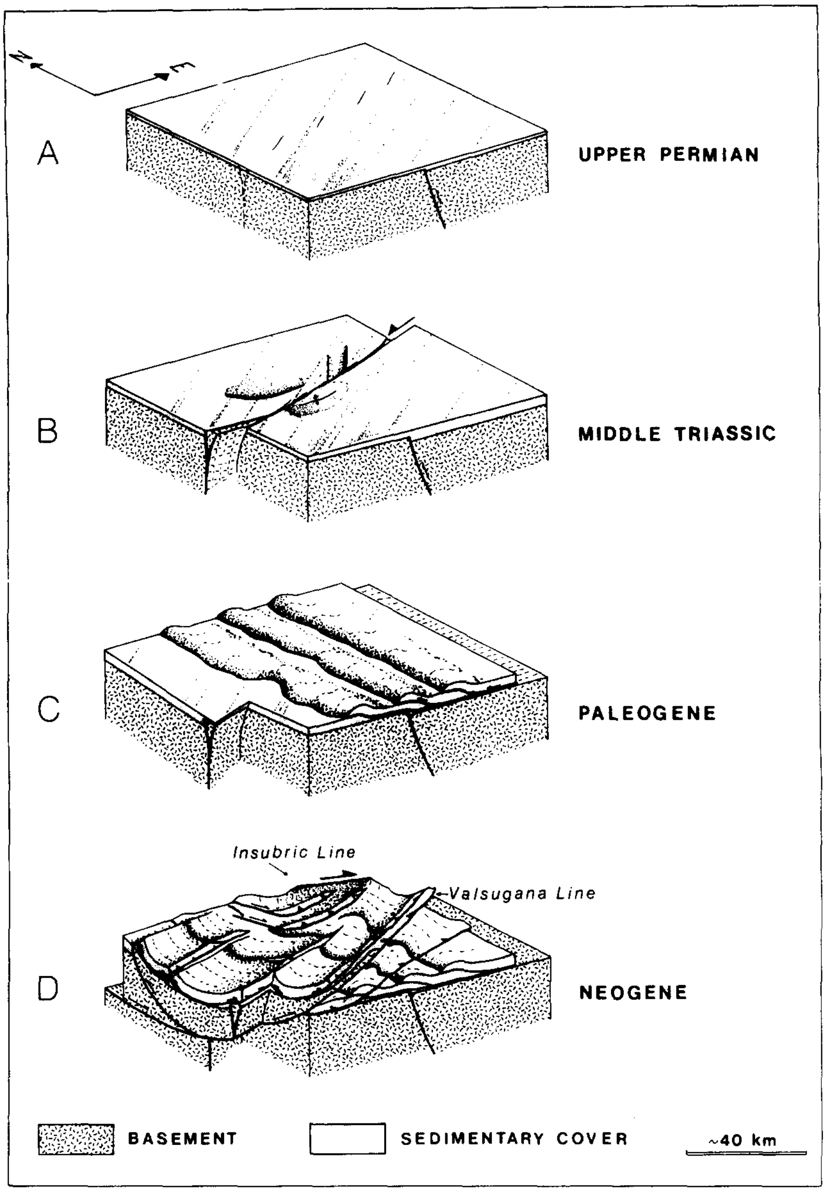

Fig. 19. Block-diagram reconstruction of the main tectonic phases in the upper crust of the Dolomites; A, start of the Permo-Mesozoic rifting; B, sinistral Middle Triassic transpression along the N70°E axis; C, Palaeogene (?) E–W compression; D, Neogene N–S compression.

mation has been injected into the sedimentary cover, forming diapiric anticlines related to deep basement deformation (Doglioni 1984a). These diapiric structures were often reactivated during the Alpine tectonic phase. Intraformational folds, with basal décollements, are also common in the evaporitic layers of the Werfen Formation (Fig. 18). Kink-bands and chevron folds are common in the well-bedded Livinallongo Formation.

THE INFLUENCE OF THE INSUBRIC LINEAMENT (PERIADRIATIC LINEAMENT)

The question of the kinematics of the Insubric Lineament (or Periadriatic Lineament, Exner 1976, Dal Piaz & Dal Piaz 1984) would require an article of its own. Here I would like to emphasize only the main aspects of its influence on the tectonics of the Dolomites.

Fig. 15. Conjugate fracture planes in the Norian Dolomia Principale linked to E–W pre-Neogene compression of the Dolomites; view from south, Gardenaccia.

Fig. 16. Small-scale pop-up shown by two complementary overthrusts in the Scythian Werfen Formation. Andraz, Dolomites.

Fig. 17. Fold in the Upper Permian Bellerophon Formation. The basal evaporitic layer forms a locus for several detachments; in the field the much stronger deformation of this unit is clear. The fold shows a penetrative ductile deformation with axial planar cleavage in the gypsum and a clear thickening of the hinge; Passo Valles, Dolomites.

Fig. 18. Intraformational fold in the Gastropod Oolite (G), member of the Werfen Formation, near a transpressive fault. The fold is detached in an underlying evaporitic layer at the top of the Siusi Member (S). Passo Rolle, Dolomites.

Many interpretations of the Insubric Lineament have postulate a long and complex history (e.g. Laubscher 1971, Semenza 1974, Ahrendt 1980, Bosellini 1981, Castellarin 1982, Castellarin & Vai 1982). Laubscher (1983) suggested that the central-eastern Alps formed a mega-flower structure of which the Southern Alps are the southern branch. In this view, Neogene compression of the Dolomites may also be related to transpression. Structural evidence supports a Neogene dextral transpressive movement. Near the fault, transpression has strongly deformed the upper crust. Flower structures lie along the Insubric Lineament (Pusteria and Gail segments) in the Karawamken zone (Laubscher 1983) and in a cross-section of the Carnian Alps (Carulli *et al.* 1981). Horizontal dextral striations along the fault to the north of the Dolomites also suggest this strike–slip movement. The Neogene conjugate strike–slip faults represent a Riedel pattern (e.g. Tchalenko 1970) related to dextral movement along the Pusteria and Gail segments of the Insubric Lineament. As noted previously, the Insubric Lineament abruptly cuts the northern margin of the Dolomites, and on the eastern side (Karawanken) this cuts the connection of the Palaeogene (?) W-vergent Dolomite tectonics with the 'root zone' (Fig. 1).

Finally I would emphasize the possibility of the presence of a crustal doubling beneath the Dolomites, suggested by the presence of a crust 50–60 km thick, Giese *et al.* (1982). This may be of pre-Insubric Lineament age, because the fault cuts Alpine nappes of the Tauern Window.

CONCLUSIONS

The region of the Dolomites underwent several different tectonic events during post-Variscan times. These may be summarized as follows.

(1) Permian and Triassic rifting phases, with a N–S trend, subdivide the Dolomites into two main domains: the Atesina Platform to the west and the Carnico-Bellunese Basin to the east (Bosellini 1965a); within these structures minor basins were emplaced.

(2) Middle Triassic sinistral transpression deformed the core of the region along N70°E trends (Stava and Trodena Lines—northern limb of the Cima Bocche Anticline) generating flower structures in the basement.

(3) Volcano-tectonic domal uplift and subsequent caldera formation occurred with the emplacement of Upper Ladinian magmas.

(4) Lower Jurassic rifting continued the subsidence of the region, which increased eastward into the Carnico-Bellunese Basin.

(5) Pre-Neogene (Upper Cretaceous–Palaeogene ?) E–W (ENE–WSW) compression generated a W-vergent (or more exactly WSW-vergent) belt in the Dolomites, which probably formed the folded foreland to the Dinaric chain. At least 10–11 km of shortening occurred in a 70 km wide E–W cross-section. The root zone for these Dinaric tectonics has since been cut by the Neogene Insubric Lineament, to the NE in the Karawanken region.

(6) In Neogene times the Dolomites formed the innermost part of a S-vergent thrust belt. The basement was thrust to the south by at least 10 km along the Valsugana Line, above the sedimentary cover of the Venetian Prealps. This generated an uplift of the region by 3–5 km. The Valsugana Line and its N-vergent backthrusts generated a pop-up in the central Dolomites; a 60 km wide synclinorium. The sedimentary cover adapted itself mainly by flexural slip and by forming triangle zones. Shortening in the sedimentary cover was about 5 km; this N–S (NNW–SSE) compression sometimes faulted and folded pre-Neogene oblique thrusts. On the north-eastern side of the Dolomites, however, the shortening of the sedimentary cover could be greater and more strictly related to the Neogene transpressive effects of the Insubric Lineament. Minor deformation linked to the Giudicarie belt is also present in the western Dolomites.

The superficial tectonics of the Dolomites formed at lower temperatures, mainly in a brittle regime.

Finally, the structure of the Dolomites is the result of all the tectonic phases of different style and orientation. Early tectonic and sedimentary structures controlled the geometry of later structures. A kinematic evolution of the main tectonic events in the upper crust of the Dolomites is proposed in Fig. 19. Only a 3-dimensional restoration can unravel the true structure of the Dolomites with the correct volume balance.

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