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The overthrusts in the Dolomites: ramp–flat systems

By CARLO DOGLIONI[1])

ABSTRACT

New field work in the Dolomites has resulted in revised ideas on several aspects of local and regional tectonics, and in particular has led to three main conclusions: 1. The "summit overthrusts" of the Dolomites region consist of ramp–flat systems starting at least from the basal levels of the sedimentary cover: the "klippen" now observable on the summits are, in general, low angle thrusts, i.e. flats, and their morphological isolation is due only to erosion; they are, therefore, structures connected with regional tectonics rather than local gravitational phenomena. 2. The inclined slopes of the Triassic carbonate platforms sometimes served as overthurst ramps; hence these inherited sedimentary geometries have influenced the tectonic evolution of the area. 3. The Dolomites were probably affected in post-Paleozoic time by at least three distinct compressional phases: a) a Middle Triassic phase (apparently sinistrally transpressive in the N70E direction) already with ramps on the clinoforms generated in the progradation of a Ladinian carbonate platform: b) a pre-early Miocene phase (middle-late Cretaceous–Paleogene?) with sigma 1 approximately E–W which was responsible for a great number of summit overthrusts; c) a post-early Miocene phase, with sigma 1 approximately N30W–N0W trending.

RIASSUNTO

Lo studio di geometrie di tipo ramp–flat nei sovrascorrimenti della regione dolomitica ha portato a tre interessanti risultati: 1. I «Sovrascorrimenti di Vetta» della regione dolomitica sono costituiti da una serie di ramp–flat che partono quanto meno dai livelli basali della copertura sedimentaria; i klippen che troviamo oggi sulle vette sono in genere sovrascorrimenti a basso angolo, cioè in flat, e la loro morfologia isolata è dovuta solamente all'erosione; i sovrascorrimenti di vetta sono quindi strutture collegate alla tettonica regionale e non sono perciò locali fenomeni gravitativi. 2. Gli slope inclinati delle piattaforme carbonatiche triassiche sono stati a volte sede di ramp per sovrascorrimenti: quindi queste geometrie sedimentarie ereditate hanno influenzato l'evoluzione tettonica della regione. 3. La regione dolomitica à stata probabilmente interessata in epoca post-paleozoica da almeno tre fasi tettoniche compressive: a) una fase medio-triassica (apparentemente transpressiva sinistra nella direzione N70E), tra l'altro con ramp già sulle clinostratificazioni prodotte dalla progradazione di una piattaforma carbonatica ladinica; b) una fase pre-Miocene inferiore (Cretaceo medio-superiore–Paleogene?) con sigma 1 circa N90E (E–W), responsabile di gran parte dei sovrascorrimenti di vetta; c) una fase post-Miocene inferiore con sigma 1 circa N30W–N0W, ad assi valsuganesi.

Introduction

This study is an attempt at demonstrating the existence of ramp–flat geometries in the Dolomites overthrusts (Fig. 1). These structures are important clues for the understanding of the structure of the Dolomites. These were only mildly deformed by Alpine tectonics, and it is therefore possible to identify the original Triassic heteropic transitions between carbonate platforms and basins. An attempt is made to understand how these

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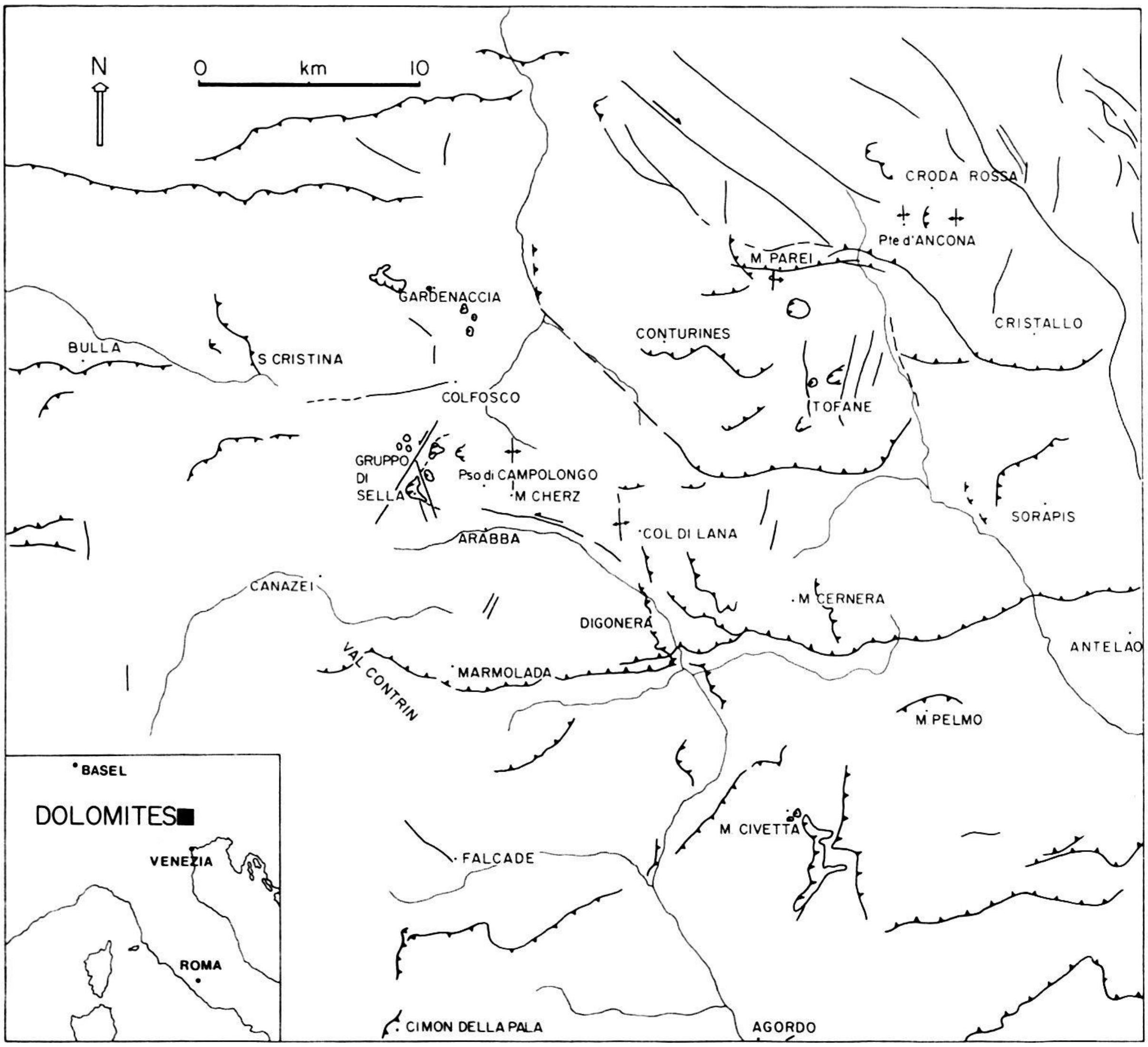


Fig. 1. Schematic map of Alpine tectonics in the Dolomites (northern Italy), showing the location of features discussed in the text and illustrated in the figures.

paleostructures might have influenced the tectonics of the Dolomites and what relations they might have had with ramp–flat geometries. Another important result of these observations concerns the relation between ramp–flat geometries and the "summit overthrusts" (Sovrascorrimenti di Vetta or Gipfelfaltungen), those enigmatic features that for years have puzzled geologists. These new local insights are used for a first attempt at a synthesis of the compressive phases of tectonics in the Dolomites.

Inherited sedimentary geometries affecting the overthrusts

Schematically, the overthrusts are transmitted upward in the stratigraphic sequence with flat–ramp–flat geometries (Fig. 2). Of course the kinematics allow structures like ramp folds (SUPPE 1983) in a simple case, or structures like duplexes or imbricate fans (BOYER & ELLIOTT 1982) in the more frequent cases. Besides, the first step in the study of the tectonics of an area is an analysis of the inherited, pre-existing geometries (LAUBSCHER

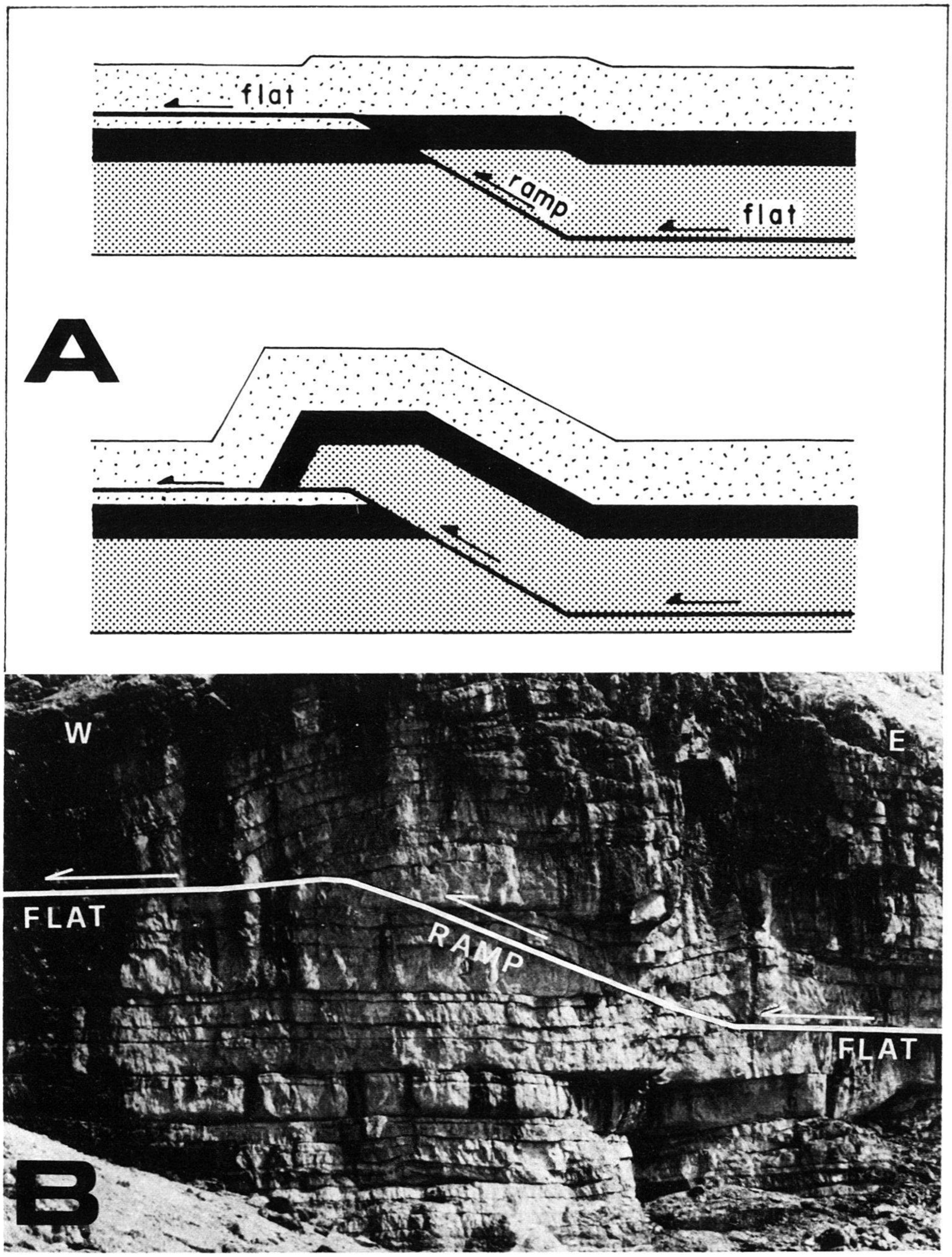


Fig. 2. A: Geometry and kinematics of an overthrust consisting of alternating flat (thrust plane parallel to bedding) and ramp (thrust plane oblique to bedding) regions, after SUPPE (1983). B: Small scale example of an overthrust with ramp–flat geometry; Rhaetian Limestone of the Piz Boè (Sella Group, Dolomites); view toward north, height of rock wall about 20 m.

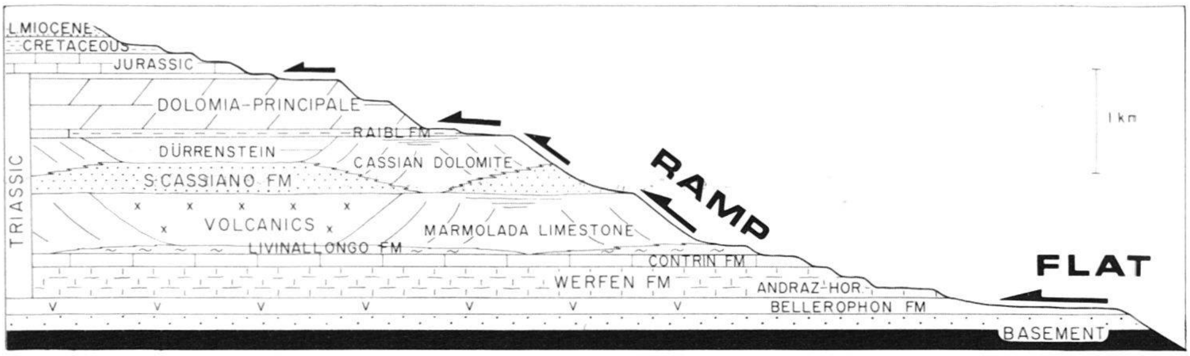


Fig. 3. Potential control on the localization of the flat and ramp segments of an overthrust related to the sedimentary succession (lithology, thickness, geometry) in the Dolomites. Basement includes Gardena Sandstone, ignimbritic plateau and metamorphic basement.

1967). The dolomitic region was very strongly deformed during Middle-Triassic times (PISA et al. 1979, BOSELLINI et al. 1982, DOGLIONI 1982, 1983, 1984). These tectonics have been related to a transpression along a N70E axis, the Stava Line–Cima Bocche Anticline lineament (DOGLIONI 1984) and must have played the role of an important inherited geometry during Alpine compressional tectonics. In addition the sedimentary architecture and the lithologies of the stratigraphic sequence have conditioned the structural evolution of the region, determining the location of the ramps and flats.

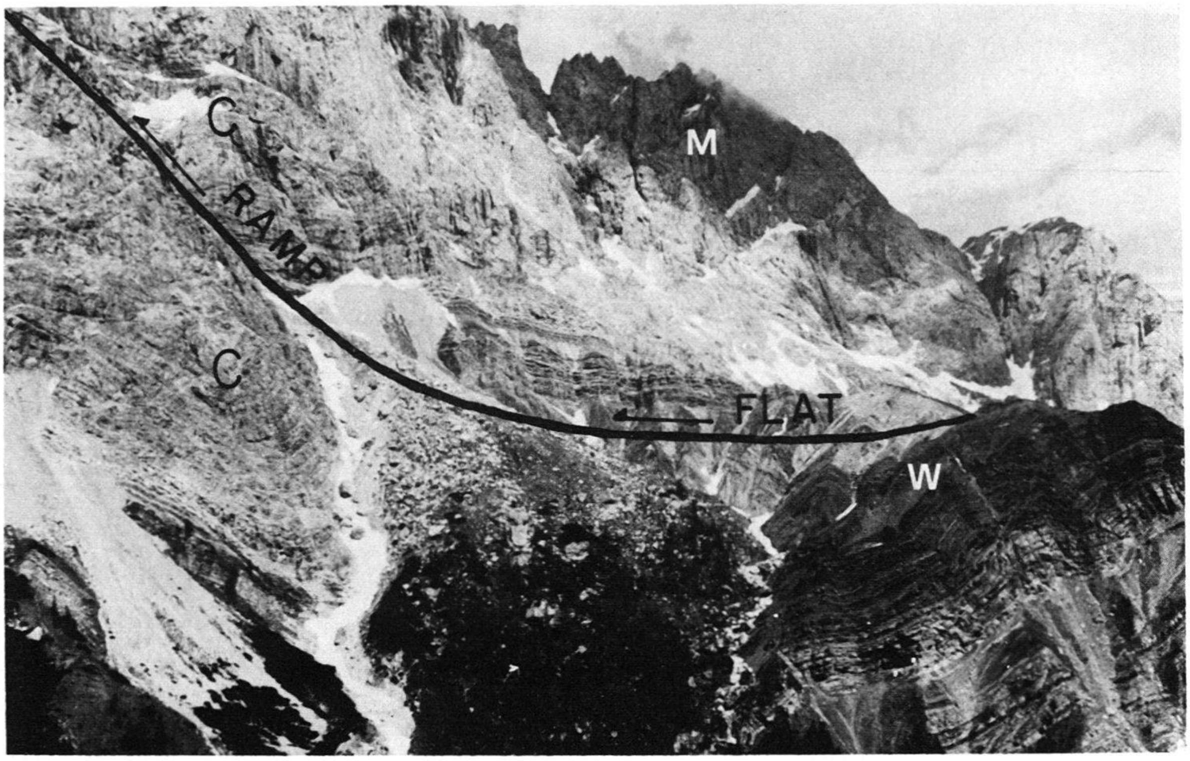


Fig. 4. Ramp–flat geometry in the Cimon della Pala overthrust, visible to the south of Passo di Rolle. The flat runs along an evaporitic horizon in the upper part of the Scythian Werfen Formation (W), whereas the ramp is in the Anisian Contrin Formation (C). The structure is affected by several additional smaller overthrusts not visible on the photo. The trailing limb of the fold of the Contrin Formation above the thrust has tensional features. M: Marmolada Limestone.

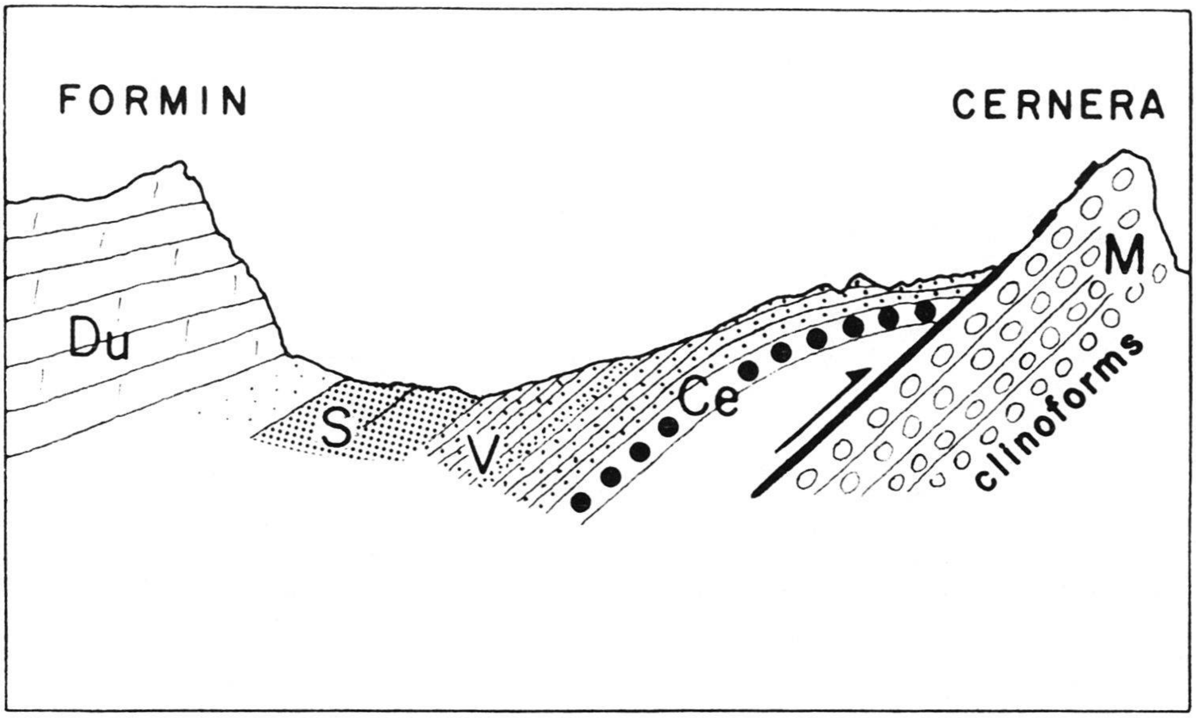


Fig. 5. The volcanoclastic unit (V: volcanic sandstones, breccias and turbidites), originally in onlap on the eastern slope of the Monte Cernera Ladinian carbonate platform (M: Marmolada Limestone) appears to be affected by a basal overthrust. This is shown by a major tectonic contact, in addition to striae and small thrusts. Note the subparallelism of (V) to the Ladinian carbonate slope in the centre of the picture. The inherited sedimentary slope clearly represents the overthrust ramp. The drag-fold depicted by a body of megabreccias (Ce: Caotico eterogeneo) supports this assumption. S: S. Cassiano Formation; Du: Dürrenstein Dolomite; white: Quaternary.

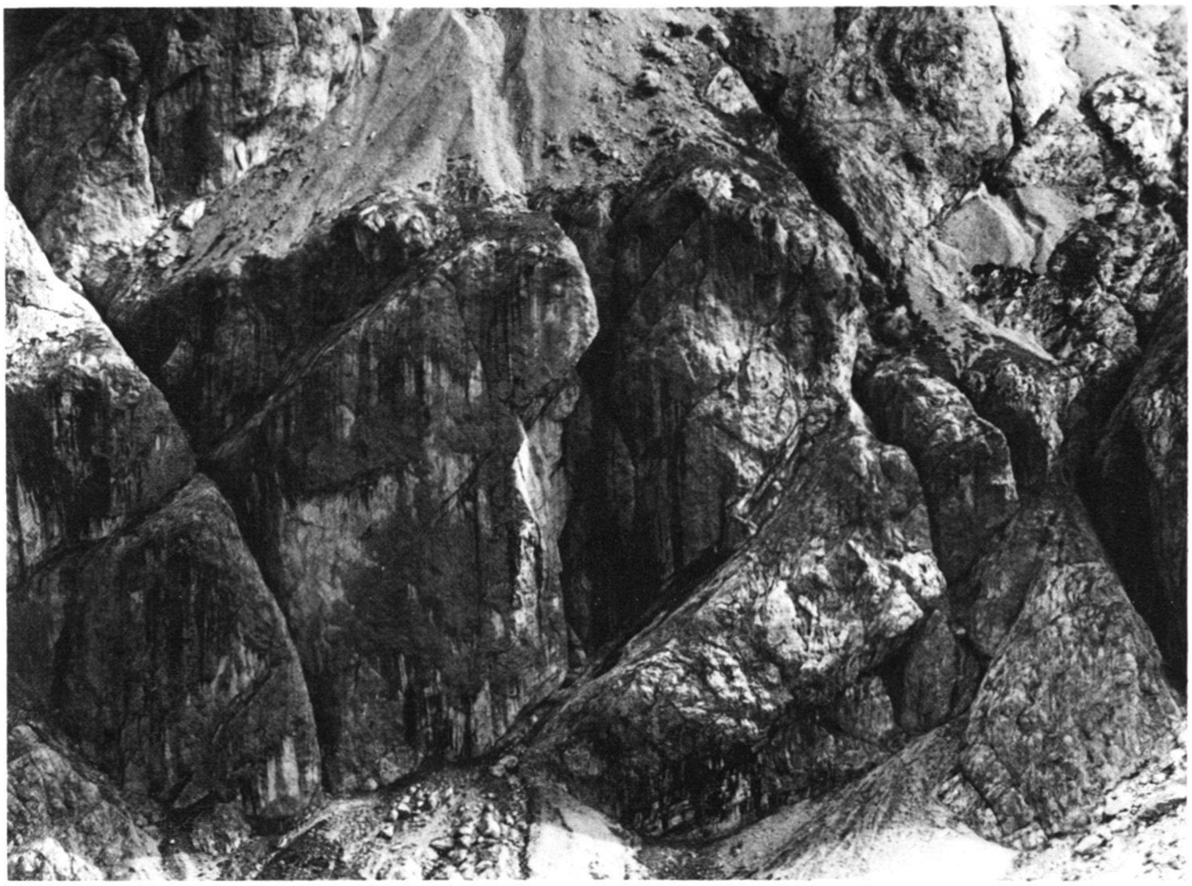
Flats: The more typical decollement horizons (flats) in the stratigraphic sequence of the Dolomites (Fig. 3) are the evaporitic levels like the "fiammazza facies" of the Permian Bellerophon Formation (gypsum, shales, marls and vuggy dolomites), the evaporitic horizons of the Scythian Werfen Formation (e.g. the Andraz Horizon, earthy dolomites, siltstones and marls) and the Carnian Raibl Beds (shales, marls, limestones, gypsum) in the central and eastern Dolomites.

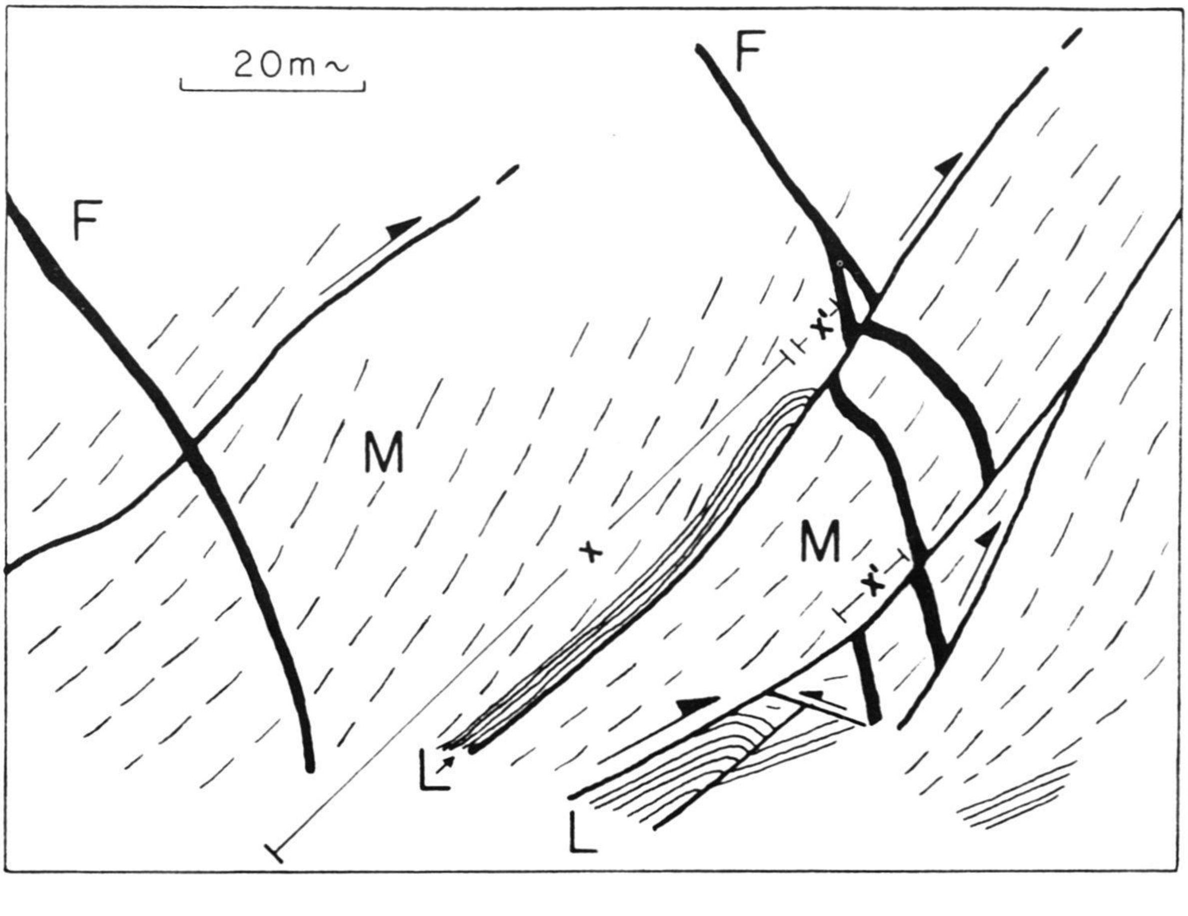
In the overthrust of the Cimon della Pala, for instance, it can be observed how an evaporitic level of the Cencenighe Member of the Werfen Formation was the seat of a flat, while the ramp ran onto the Anisian carbonate platform (Contrin Formation, Fig. 4). Other important overthrusts have flats in the Raibl Beds, as for instance in the Alpe di Fanes, Conturines, Cristallo, Sorapis, Antelao, Pelmo, etc., similar to what observed in the Bergamasc Alps (LAUBSCHER 1985). Other horizontal overthrusts pass between formations with strong lithologic differences (e.g. dolomite–marl, or limestone–shale, or limestone–volcanoclastic sandstone transitions, etc.).

Ramps: The overthrust angle in homogeneous material is between 45° and 0°, commonly 20°–30° (HAFNER 1951, PRICE 1959) and a dip very close to this value is often observed in the original slopes of the Ladinian and Carnian carbonate platforms of the Dolomites (Fig. 3). The slopes were covered by onlapping volcanoclastic sediments in the case of the Ladinian carbonate platforms, or by carbonate sediments in the case of Carnian carbonate platforms.

These Triassic slopes are excellently preserved (BOSELLINI 1984) because subsequent deformation has been mild. The slopes represented important planes of mechanical weakness during the compressional phases in Triassic as well as in Cretaceous–Tertiary times. This is demonstrated by their frequent tectonization. In particular they became the seat of overthrust ramps. Thus the volcanoclastic–Ladinian carbonate slope contacts in many places show small thrust faults, striations and a disharmonic attitude of the volcanoclastic sediments, all of which indicate that these latter moved upward, i.e. were thrustsed onto the platform slope (compare Fig. 5). This situation is shown, for instance, by the upthrust of the volcanoclastic sediments along the slope ramp (Ladinian) at Cernera and at Piz del Corvo (Fig. 5). In order to produce the geometry shown by this figure, one has to hypothesize a decollement (flat) surface at the base of the volcanoclastic sequence, and an overthrust ramp coinciding with the Ladinian platform slope. Although

Fig. 6. Overthrusts emplaced on the clinoforms of a Ladinian platform slope. This outcrop is located about 1 km southeast of the Rifugio Contrin, at the head of the Contrin Valley. Some overthrusts appear to be emplaced on the megabreccias' clinoforms (dashed lines pattern on drawing) of the Ladinian carbonate platform (M: Marmolada Limestone). The Livinallongo Formation (L), a basinal formation heteropic of the megabreccias, was thrusted along ramps following the pre-existing sedimentary geometry of the clinoforms. In order to bring the Livinallongo Formation back to its original basinal position (necessarily the seat of the flat) one should move one of the S-vergent overthrusts by a distance of at least X. However, the volcanic dikes (F), Late Ladinian in age, are offset only for a distance X'. Hence the distance X–X' should be a pre-dike shortening of Middle Triassic age. The amount X' is perhaps the amount of Alpine reactivation of the overthrust. At the right side of the picture there is a wedge of Marmolada Limestone between two dikes joined at the top. The wedge is faulted by the post-dikes reactivation of the overthrusts. The overthrust at the left side of the picture does not appear to have occurred along the megabreccias' clinoform, nor to have been reactivated after the Triassic dike intrusion. The overthrusts in the centre and on the right side are more steeply inclined upward, perhaps due to a steeper orignal clinoform. Please refer to Figure 7 for a kinematic reconstruction of the structure.

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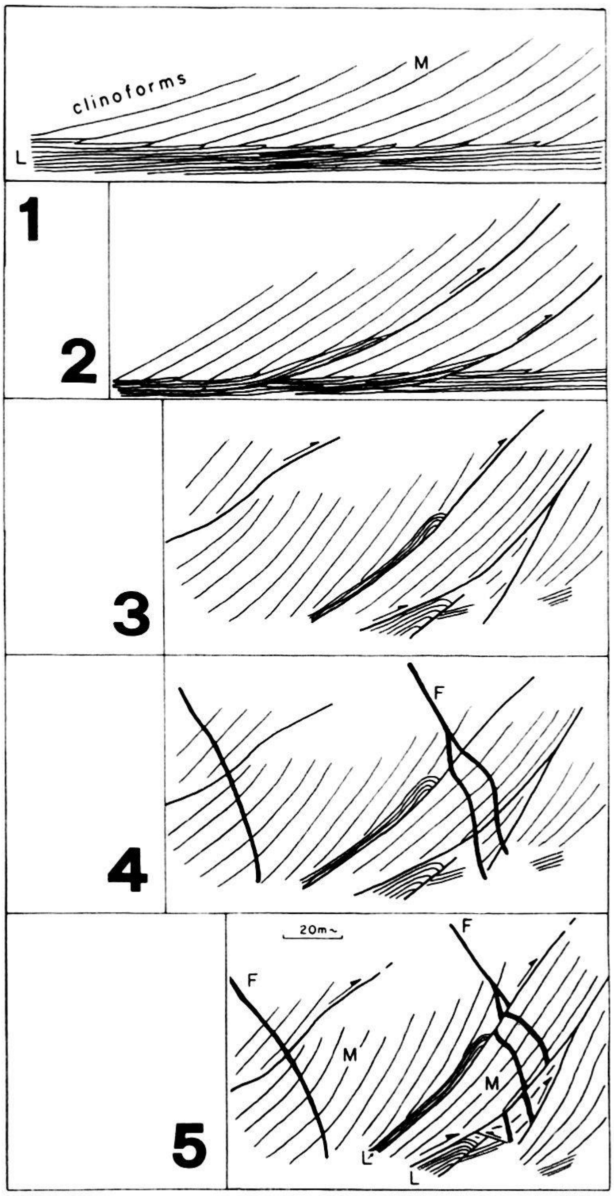

Fig. 7. Tentative kinematic reconstruction of the structure in the Upper Contrin Valley (see Fig. 6): 1. facies heteropy of the Ladinian carbonate platform megabreccias (M: Marmolada Limestone) with the basinal sediments of the Livinallongo Formation (L). Note the megabreccias' clinoforms; 2. at the onset of compression the hangingwalls of the thrusts use the clinoform planes as ramps. The Livinallongo Formation, that must have been detached along a bedding plane (flat), is pushed onto the ramp; 3. the overthrust to the left of the picture does not appear to be emplaced along the clinoform and could therefore have been active after the structure to the right was already formed; 4. dikes (F) of the Upper Ladinian cut across the overthrusts, thus dating them as preceding the intrusion; 5. a further compressive event (Alpine?) remobilized the overthrusts to the right. The wedge of Marmolada Limestone (M) between the two dikes joining higher up is slightly offset. This is the actual situation of Figure 6.

the amount of displacement may not have been very great (probably less than 1 km), it was evidently sufficient to produce a subparallel position of the volcanoclastic sequence with respect to the ramp (Fig. 5). Differential compaction of the volcanoclastic sequence relative to the carbonate bodies does not appear to be sufficient to account for the present structural situation. Furthermore, e.g. at Piz del Corvo, the basinal Livinallongo Formation has also risen along the Ladinian platform slope, again by thrusting.

Another interesting structure can be observed at the head of the Contrin Valley. Here, a series of overthrusts appears to have been emplaced along the clinoforms of the megabreccias (Marmolada Limestone) connected with the progradation of the slope of the Costabella Ladinian carbonate platform toward the basinal area to the north (Fig. 6 and 7). This is documented by the present-day position of the basinal Livinallongo Formation along the thrusts. In this spectacular outcrop it is possible to observe that the larger part of the overthrusts (X) occurred before the intrusion of the Middle Triassic volcanic dikes. Whereas the Middle Triassic dikes have been displaced only about 10 m by late Triassic or Alpine movements, a larger amount of displacement can be calculated for the pre-volcanic formations. Restoration of the depositional geometry by kinematic inversion (placing the basinal Livinallongo Formation back at the foot of the slope) results in a minimum overthrust of some 80–100 m preceding the emplacement of the dikes (Fig. 6 and 7).

Another example of overthrust with ramp on the slope of a Triassic carbonate platform is visible at the Passo di Campolongo (Fig. 8 and 9). Other typical ramps of the overthrusts in the sedimentary cover of the Dolomites develop in the Contrin Formation, in the Dolomia Principale and in the Liassic Calcari Grigi (Fig. 3).

Summit overthrusts

Typical ramp–flat geometries are observable in the summit overthrusts of the Dolomites. Several studies described and discussed the summit overthrusts (Sovrascorrimenti di Vetta or Gipfelfaltungen, FURLANI 1909, REITHOFER 1928, CASTIGLIONI 1931,

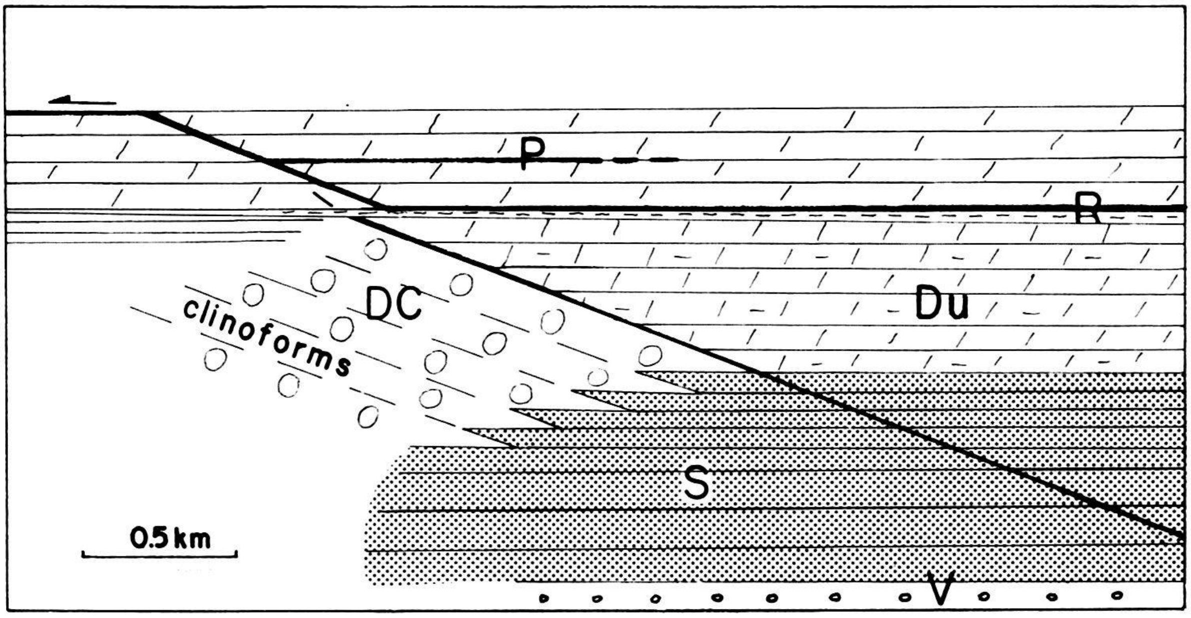

Fig. 8. Reconstruction of the inherited Triassic depositional geometry that has conditioned the compressional tectonics now visible in the eastern section of the Sella Group (Passo di Campolongo, see Fig. 9). The heavy black line is the location of successive ramps and flats of the overthrust. The slope of the Carnian carbonate platform (DC: Cassian Dolomite) is a seat for a ramp, while the base and the top of the Dolomia Principale (P) are seats for flats. The Dürrenstein Dolomite (Du) was sedimented in onlap onto the Carnian slope (A. Bosellini, pers. comm., DOGLIONI 1982). S: S. Cassiano Formation; V: volcanoclastic sandstones; R: Raibl Beds.

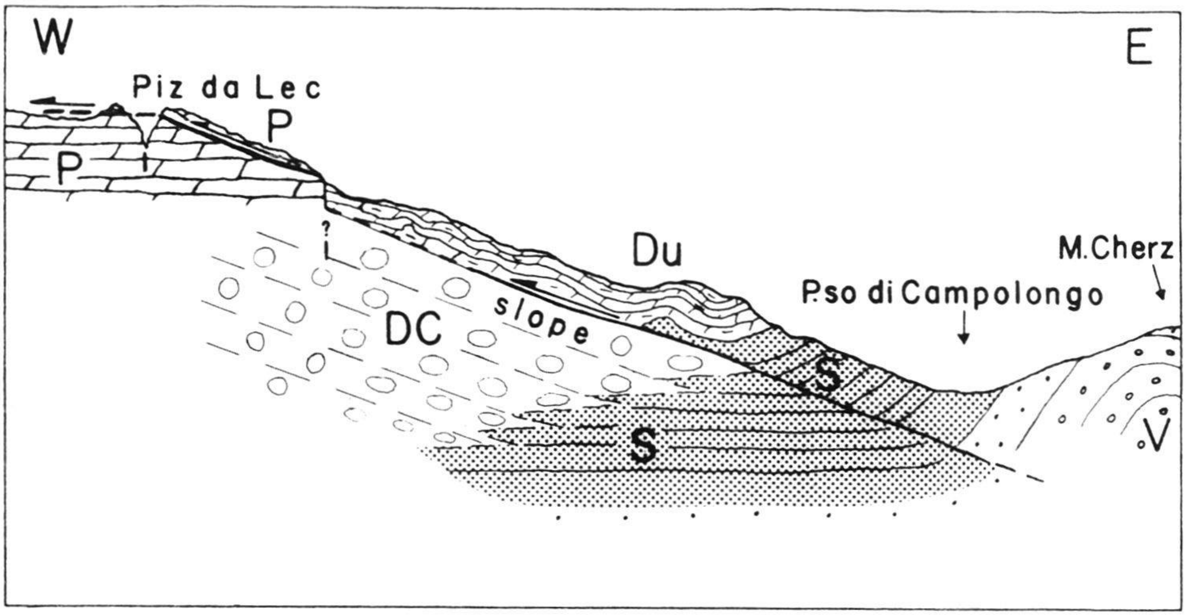

Fig. 9. Passo di Campolongo section. Note how compression is transmitted from an anticline on Monte Cherz (to the right), with volcanoclastic Lower Carnian sandstones in its core (V), to an overthrust ramp above the original slope of the Carnian carbonate platform (DC: Cassian Dolomite). The Dürrenstein Dolomite (Du), originally deposited in onlap on the slope (see Fig. 8), was pushed up along this slope. Also the S. Cassiano Formation (S), the heteropic basinal equivalent of the Cassian Dolomite, has advanced a small distance up the slope. The overthrust continues in a ramp onto the Norian Dolomia Principale (P), flattening at its top, where it underlies the small klippe near Piz da Lec. Picture taken from Porta Vescovo looking northward.

Klebelsberg 1935, Leonardi 1955, Accordi 1955, 1957, Colacicchi 1960). Until now these structures were interpreted as local gravitational phenomena. It is now possible to demonstrate that in the majority of the cases the summit overthrusts are in fact, simple overthrusts with a ramp–flat geometry (Fig. 2).

At the Passo di Campolongo (Fig. 8, 9 and 10), it can be observed how the deformation gradually proceeds from the formations laterally adjacent to the Sella Massif to the highest points of the latter, thus leading to the famous summit overthrusts. From an

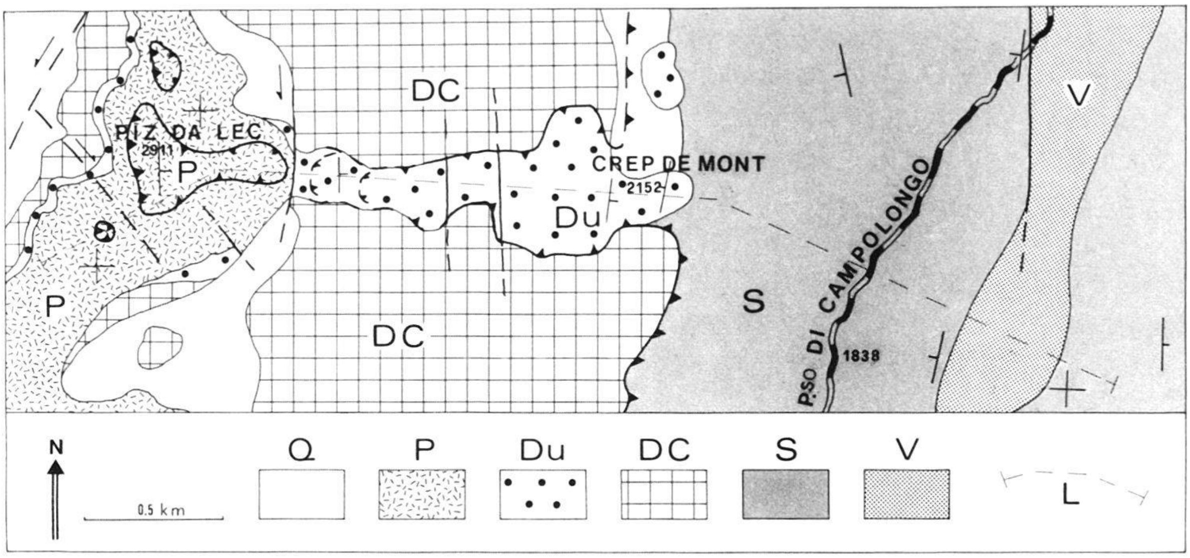

Fig. 10. Geologic map of the Passo di Campolongo area. L: section line of Figure 8 and 9; V: volcanoclastic sandstones; S: S. Cassiano Formation, Civetta Member; DC: Cassian Dolomite; Du: Dürrenstein Dolomite; P: Dolomia Principale; Q: Quaternary. The E–W compression is evidenced by an anticline east of the Campolongo Pass and by a ramp onto the slope of the Cassian Dolomite. It continues westward with an overthrust in the Dolomia Principale. The vertical transcurrent faults are younger with respect to the E–W compressional phase, but did not affect the older structures noticeably.

anticline on Monte Cherz (perhaps a fold connected with a covered ramp), the overthrust runs onto the inclined slope of the Carnian carbonate platform of the Sella, slightly moving the heteropic basinal S. Cassiano Formation upslope. The Dürrenstein Dolomite (Fig. 8), originally in an onlap position on the Carnian platform slope (A. Bosellini, pers. comm., Doglioni 1982), has also risen along the pre-existing, inherited slope (ramp). The thrust plane has a dip of about 30° on the Carnian slope, diminishing to 25° in the Dolomia Principale and to 10–0° at the top of the latter thus progressing from a ramp to a flat. This configuration is responsible for the typical morphology of the summit overthrust (Fig. 9). Further, the amount of rise of the formations along the slope does not appear to explain the entire shortening visible higher up, on the top of the Sella Group (Piz Boè). This may indicate that ramp and flat systems occurred also at levels above the Carnian slope, but were later eroded. From a point above Colfosco, in the valley leading to the Rifugio Puez, it is possible to observe in the high walls of the Val de Mesdì, how the overthrust that starts from the Passo di Campolongo and reaches the top of the Piz da Lec in a ramp, changes into a flat at the top of the Dolomia Principale, and can be projected to the flat of the small klippen atop of the Cima del Pisciadù on the western flank of the valley. It is clear that the connection was eroded as the Val de Mesdì was forming.

In the Sella Massif the summit flat follows not only the top of the Dolomia Principale but ramps up to the top of the Rhaetian Dachstein Limestone, the top of the Dogger Rosso Ammonitico and the top of the early Cretaceous Puez Marls, always through small connecting ramps between one decollement horizon and the next. The overthrust planes as seen frontally on the Sella Group, i.e. to the west of the top of the Piz Boè, are irregular and undulating, changing in a short space the seat of their movement (Fig. 11), resulting in oblique directions of transport (cf. Butler 1982).

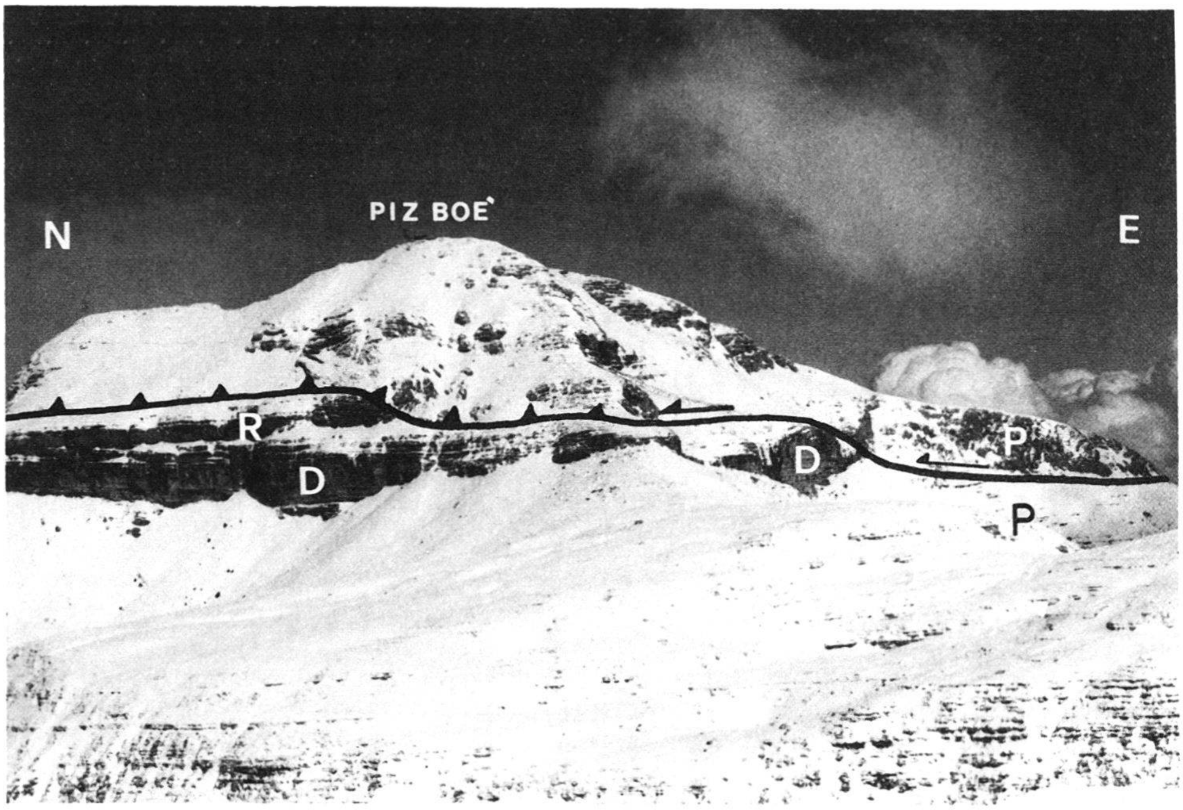

Fig. 11. Piz Boè (Sella Group) seen from Sass Pordoi, looking northeast. The black line indicates the basal thrust plane of the summit overthrust of Piz Boè. On the left side of the picture the overthrust is shown in frontal section (black triangles); on the right side it is in lateral section. In frontal section, the overthrust is seen as a wavy plane covering the Dogger Ròsso Ammonitico (R) as well as the Rhaetian Dachstein Limestone (D). An oblique movement along the plane occurred at the transition between the two units. On the right side of the photograph the lateral section shows the flat–ramp–flat geometry of the W-vergent overthrust. The first visible flat is at the top of the Norian Dolomia Principale (P). After a small ramp, the following flat is on top of the Dachstein Limestone. Other small overthrusts (not shown) present above the basal overthrust form duplex structures within the summit klippe. Well developed ramp folds are therefore impossible to see.

The compressive structures of the Gruppo di Sella, with N–S axis, appear in connection with anticlines and overthrusts (Col di Lana Anticline, Digonera Line) present to the east of the massif (Fig. 1), that are involving the basal evaporitic levels (Bellerophon Formation, Upper Permian) of the sedimentary sequence. On the Sella Massif it is therefore possible to observe how the summit overthrusts are gradually connected to deeper structures located on one of its flanks through a continuum of flat–ramp–flat systems. A gravitational origin for them can thus be excluded.

In the summit overthrust of the Civetta Group it is possible to recognize flat–ramp–flat geometries too, degrading eastward within the stratigraphic sequence. The summital W-vergent overthrust (with N–S trending fold axis) is generally subhorizontal (in flat) and is connected with an overthrust ramp (30°) to the east of the massif (Fig. 1). The present-day occurrence of the summit overthrust mass as an isolated klippe appears to be only a consequence of the erosion which has cut it off from its root to the east.

We can observe similar geometries in the Puez–Gardenaccia Group. Ramps in the Dolomia Principale flatten out toward the top of this formation and horizontal thrusts occur along the top of the Cretaceous marls. In this massif summit overthrusts degrade within the stratigraphic sequence both eastward (with N–S trending fold axis) and northward (with E–W trending fold axis). This probably indicates two distinct compressional tectonic phases. As one climbs from Colfosco towards the Rifugio Puez, one can also observe how the Dolomia Principale in the footwall of the summit overthrusts was affected by compressions of the same directions as the overriding blocks, with complementary fracture planes dipping about 30°. As in all other summit overthrusts, the overriding block is more severely tectonized than the footwall, a situation which must be expected if one considers the deformation to which a rock mass is subjected during its progress through ramp and flat stages, in addition to drag phenomena.

It is possible to see the same ramp–flat geometry in the Tofana III: the horizontal basal overthrust (in flat) of the summit klippe is connected with a ramp thrust within the stratigraphic sequence more to the east (Fig. 12). A similar development is observed in the Croda Rossa and in the Punte d'Ancona. Ramp–flat geometries in overthrusts are also recognizable in the sections along and to the south of the Valsugana Line, as visible for example in the cross sections of SEMENZA (1959), BIANCHIN & SEMENZA (1965) and SEMENZA et al. (1984). Locally and in areas isolated by erosion, these geometries are quite similar to those of the summit overthrusts proper.

A very important Lower Miocene conglomerate at Monte Parei (CROS 1966, 1978) allows us to date two different tectonic phases that compressed the Dolomite region. This conglomerate (Aquitanian beach sediments) sutures a large W-vergent isoclinal recumbent fold in Liassic beds (sigma 1 about E–W like most of the summit overthrusts), while the conglomerate itself is folded and faulted by E–W trending structures (sigma 1 about N–S). Here the Miocene sediments postdate not only an earlier compressive tectonic phase (with N–S trending axis), but also a clear erosional surface, since in the nearby Fanes plateau the series continues up to the Lower Cretaceous.

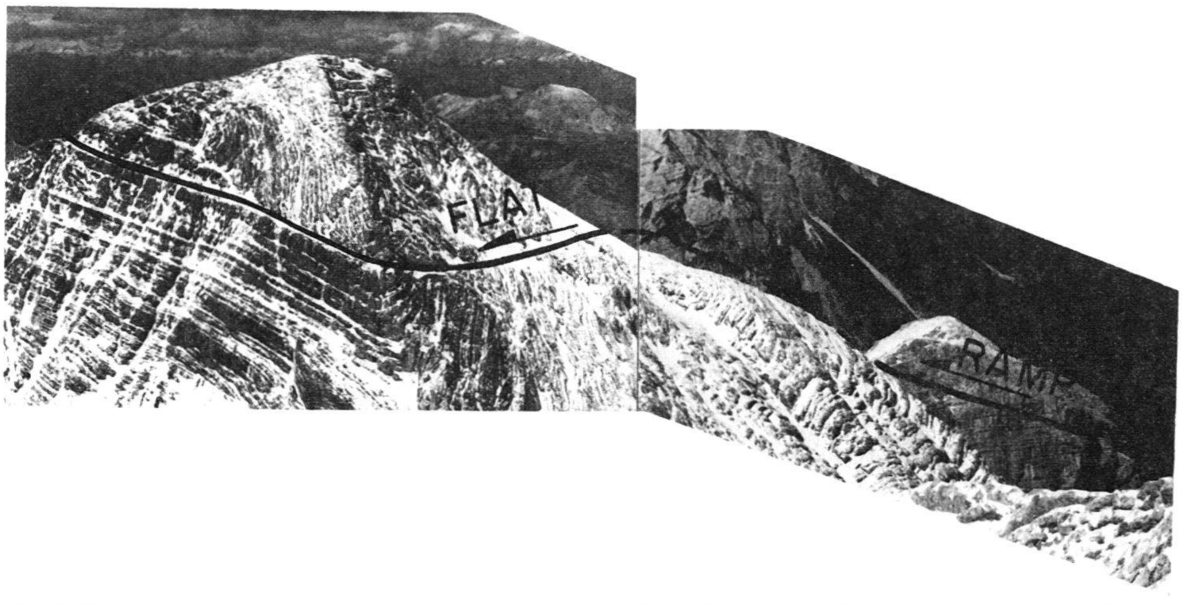

Fig. 12. Ramp–flat geometry in a W-vergent overthrust on Tofana III. The ramp is largely eroded, thus giving rise to a small klippe (summit overthrust). Within the underlying sequence other structures of this type are present. Photo taken from Tofana II, looking northward.

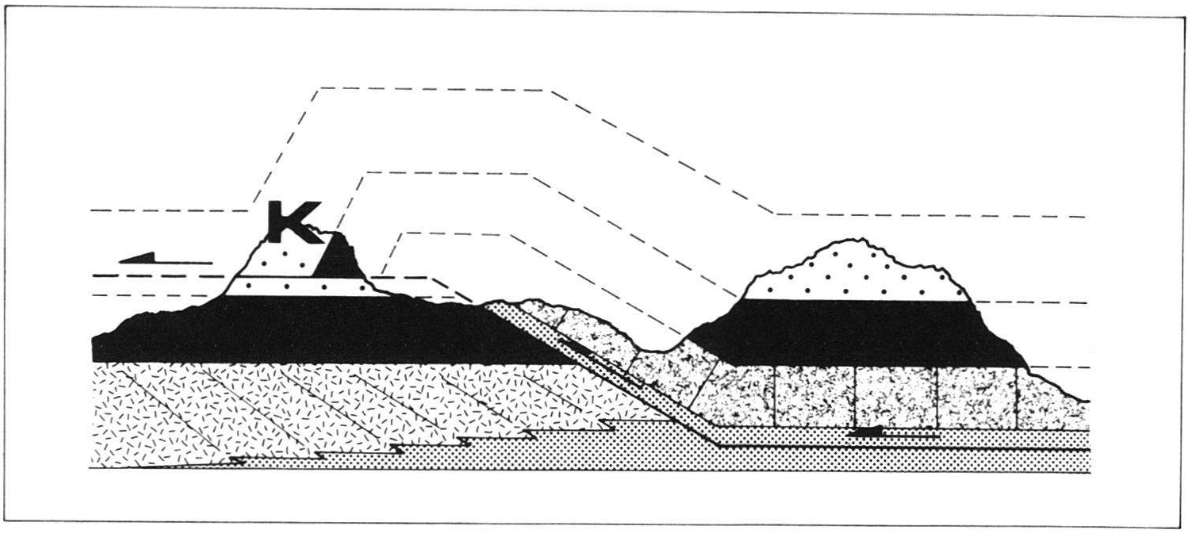

Fig. 13. Schematic cross section showing the origin of a klippe (K), or summit overthrust of the Dolomite region. The dashed part of the structure has been eroded.

Conclusions

The inherited sedimentary features, such as the slopes of the Triassic carbonate platforms, and the occurrence of evaporitic or marly–shaly horizons have noticeably affected the tectonics of the Dolomites respectively acting as ramps and flats in overthrusts.

As an example, at Passo di Campolongo (Sella Group) it can be observed how a ramp is present along the slope of a Carnian platform (Cassian Dolomite), grading upward through a slightly less steep ramp in the Dolomia Principale, into a flat at the top of the latter, thus generating a typical summit overthrust (Fig. 9). The genesis of the summit overthrusts is therefore ascribed to regional tectonism affecting the entire sedimentary cover (including the basement), and not to gravitational phenomena. The summit overthrusts (Sovrascorrimenti di Vetta or Gipfelfaltungen) are therefore areas of overthrust flats. Their apparent disconnection from the structures present within the sequence adjacent to the carbonate massifs is due only to the erosion that has preserved the rigid platforms and the klippen located on their tops (Fig. 13).

The structural data, such as the orientation of fold axes related to the summit overthrusts and within the entire underlying sedimentary sequence, microstructures, transcurrent conjugate planes, ramps on Triassic slopes and across competent formations, all seem to indicate that the Dolomites underwent at least two Alpine tectonic compressional phases: one of pre-early Miocene (late Cretaceous–Paleogene?) age with sigma 1 directed approximately N90E, and one of post-early Miocene age with sigma 1 approximately N30W–NS. The structures of the older phase are W-vergent, those of the younger S-vergent. The pre-early Miocene structures with axes about N–S are located to the east of a large N–S anticlinal structure, the Bolzano Anticline, which has in its core Permian volcanics tectonically belonging to the basement.

Finally, the Triassic overthrusts of the Val Contrin support the presence of Triassic compressive tectonics in the central Dolomites, perhaps connected with a sinistral transpression along the alignment Stava Line–Cima Bocche Anticline (Doglioni 1984).

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