GEOMORPHOLOGICAL FEATURES OF THE DOLOMITES (ITALY)

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Abstract

The Authors, after a brief geographical and geological setting, describe the main geomorphological features of the Italian Dolomites which show a significant variety of landforms and surficial deposits, due to the spatial distribution of very different geological formations and to the complex Quaternary evolution of the region. Structural landforms, glacial, periglacial, gravitational landforms and deposits and karst phenomena are reviewed and illustrated with some examples.

Key words: Geomorphology, Dolomites.

Riassunto

Aspetti geomorfologici delle Dolomiti (Italia). Gli Autori, dopo un breve inquadramento geografico e geologico, descrivono i principali aspetti geomorfologici della regione dolomitica che, per la distribuzione spaziale di formazioni geologiche assai differenti fra loro e per la complessa evoluzione quaternaria subita, presenta una notevole varietà di forme e di depositi superficiali. Vengono passate in rassegna ed illustrate con una serie di esempi le forme strutturali, le forme e i depositi glaciali, periglaciali e gravitativi ed infine i fenomeni carsici.

Termini chiave: Geomorfologia, Dolomiti.

1. INTRODUCTION

The Dolomites, also known as the "Dolomite Alps", are located in the eastern sector of the Alpine chain (Fig. 1). They are bounded to the north by the Rienza River, on the east by the Piave River, on the south by the Brenta River and the terminal section of the Fersina Torrent and on the west, for a limited extension, by the Isarco River (between Bressanone and Bolzano) and then by the Adige River. These boundaries correspond to the Pusteria Valley, Piave Valley, Val Sugana and Adige Valley, respectively. In accordance with the most recent geographical division of the Alps into 220 groups (*Bertoglio & De Simoni*, 1979), the following mountain groups belong to the Dolomite Alps (Fig. 2): Pùtia Group (2.874 m), Croda Rossa Group (3.139 m), Dolomiti di Sesto (3.152 m), Odle Group (3.025 m), Tofàne Group (3.243 m), Cristallo Group (3.216 m), Antelào-Sorapìs Group (3.263-3.205 m), Catinaccio Group (3.004 m), Sassolungo Group (3.181 m), Sella Group (3.151 m), Marmolada Group (3.342 m), Dolomiti di Zoldo (M. Pelmo, 3.168 m and M. Civetta, 3.218 m), Pale di S. Martino Group (3.193 m), Latemar Group (2.846 m), Cima d'Asta and Lagorai Group (2.847-2.754 m) and the Vette Feltrine Group (2.334 m).

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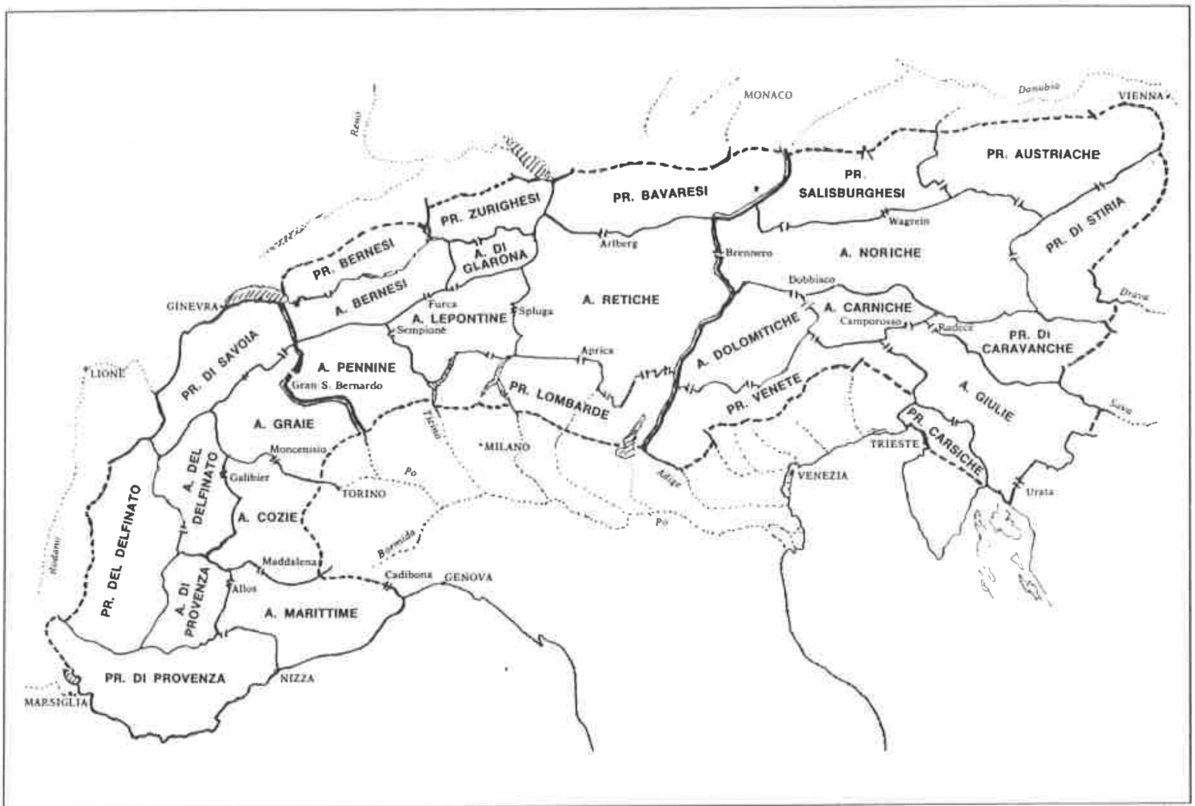

Fig. 1 - The large sectors of the Alpine system (after *Bertoglio & De Simoni*, 1979).

The morphological features of the Dolomites are the result of the complex geomorphological evolution particularly effective since the end of the last glacial period (Würm) and are at the same time closely connected with the tectonic history of the region. The most typical features will be described below with reference to the morphogenetic factors which led to their modelling.

2. GEOLOGICAL SETTING

From a geological point of view, the Dolomites belong to the Southern Alps, a segment of the African continental margin which had been deformed from the Late Cretaceous to the Quaternary. Deformations had an early European vergence and an African vergence during the Tertiary. Two thrust belts are evident to the West and to the East of the Trento plateau.

The stratigraphic sequence consists of a Permo-Mesozoic sedimentary succession unconformably covering a Hercinian crystalline basement (Fig. 3).

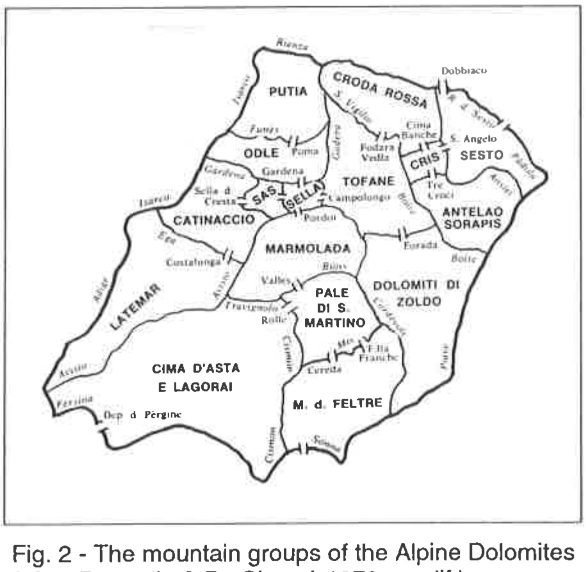

Fig. 2 - The mountain groups of the Alpine Dolomites (after *Bertoglio & De Simoni*, 1979; modif.).

The Crystalline Basement, which crops out at the northern and southern border of the Dolomites (respectively along the Pusteria Valley and in the surroundings of the Cima d'Asta massif), consists of phyllites, micaschists and paragneisses dating back to the Carboniferous (Fig. 4).

Permian volcanic rocks, mainly represented by rhyolites, rhyodacites and dacites (also known as "*porfidi quarziferi*"), cover a wide area of the south-western sector of the Dolomites, reaching the thickness of 1.500-2.000 m in the Adige Valley. These rocks are partially overlain by sedimentary rocks deposited in an environment evolving from fluvial to sabkha, to lagoonal and finally to shallow marine conditons. The principal geological formations corresponding to this period (Permian to Lower Anisian) are the Arenarie di Val Gardena (red sandstones), the Bellerophon Formation (black bituminous limestones with white gypsum beds) and the Werfen Formation (marly limestones, oolitic limestones and fine-grained red sandstones); these formations widely outcrop throughout the Dolomites.

The succession continues with the Triassic cycle (*Bigi et al.*, 1990), which consists of dolomites and limestones etheropic with volcanic rocks. After an Anisian uplifting the Dolomitic region began to sink with increasing rates, which determined a total subsidence of about 1.000 metres in four millions years at the beginning of the Ladinian. As a consequence, in a tropical warm sea situation, "reefs" grew rapidly with rates corresponding to that of subsidence, thus forming huge carbonate platforms and deep lateral basins. These platforms are at present witnessed by relevant mountain groups like Latemar, Marmolada, Pale di S. Martino, Sciliar, Alpe di Siusi, Catinaccio, Pùtia and Odle, all composed of Sciliar Dolomite.

During the Upper Ladinian the Dolomites were affected by an important magmatic activity, which led to the formation of two major volcanic apparatuses emerging from the sea, one near Predazzo and the other in the vicinity of the Monzoni mountains. Basalt and andesite lava flowed into the sea partly covering the basinal sediments of the Livinallongo Formation and intruding in fractures cutting the carbonatic platforms. These are dark brown volcanic rocks which are clearly visible at the Alpe di Siusi in Val Gardena, above Canazei and around Predazzo. Spectacular dykes crop out in the Costabella and Latemar groups.

After a marine regression which led to a partial erosion of the volcanic rocks, a new generation of reefs and carbonatic platforms developed in the Carnian; these are represented by the massive Dolomia Cassiana, whilst the basin sediments are mainly ascribable to the San Cassiano Formation which consists of resedimented calcarenites and extrabasinal siliciclastics. The most relevant outcroppings of Dolomia Cassiana coincide with large mountain groups like Sciliar, Sassolungo, Gardenaccia, Sella, Pale di S. Martino, Civetta and Lagazuoi.

During the Upper Carnian another carbonatic formation was sedimented laterally to the Dolomia Cassiana, that is the well-stratified Dürrenstein Formation which filled up the Carnian basins. On the top of the wide and flat area thus formed the Raibl Formation was deposited in the Upper Carnian; it consists of polychrome shales, limestones, marls, sandstones and conglomerates with dolomite intercalations (50 to 60 m thick). Typical outcroppings are located at Falzarego Pass, Lastoni di Formin and Tre Croci Pass.

At the beginning of the Norian age the former coastal plain was submerged due to a marine ingression; the whole region became a tidal flat where relevant thicknesses (up to 1.000 m) of well-stratified dolomites were built up, constituting the Dolomia Principale. This

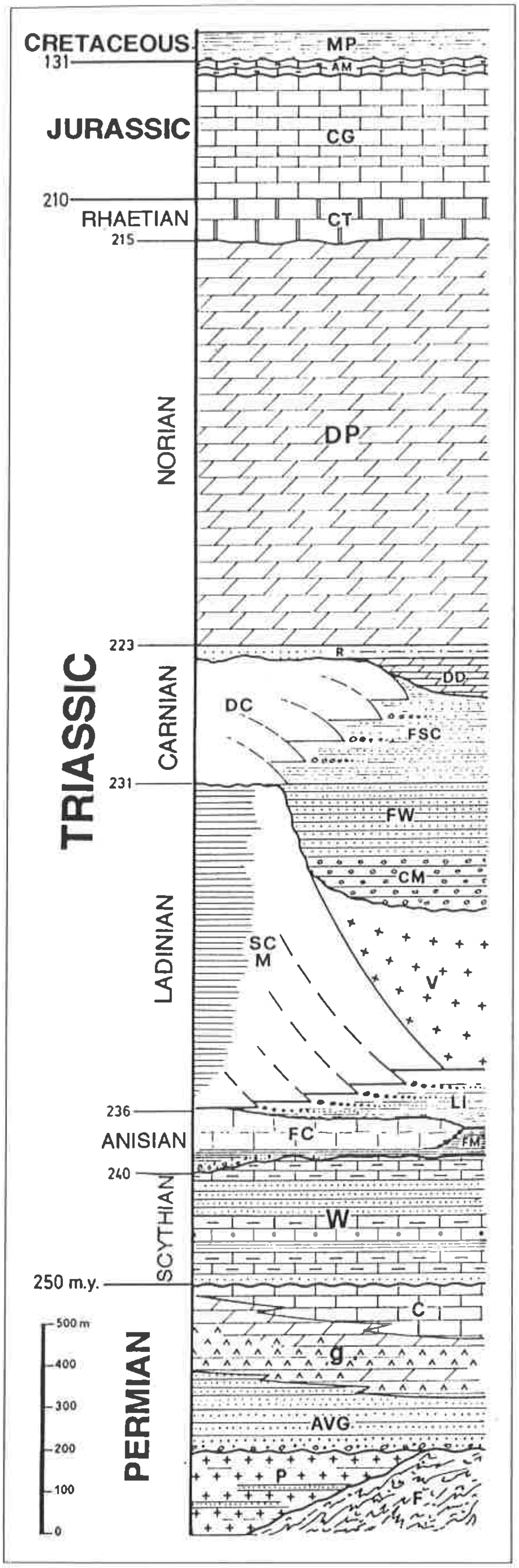

Fig. 3 - Stratigraphic sequence of the Dolomites. Legend: F) Crystalline Basement; P) volcanic rocks ("porphyries"); AVG) Arenarie di Val Gardena; g+c) Bellerophon Formation; W) Werfen Formation; FM) Moena Formation; FC) Contrin Formation; Li) Livinallongo Formation; V) volcanic rocks; M) Marmolada Limestone; SC) Sciliar Dolomite; CM) Marmolada Conglomerate; FW) Wengen Formation; FSC) San Cassiano Formation; DC) Dolomia Cassiana; DD) Dürrenstein Dolomite; R) Raibl Formation; DP) Dolomia Principale; CT) Dachstein Limestone; CG) Calcari Grigi; AM) Ammonitico Rosso; MP) Puez Marls (after *Panizza*, ed., 1988).

formation is largely represented in the Belluno and Cadore Dolomites in well-known mountain groups such as Tre Cime di Lavaredo, Cristallo, Pomagagnon, Sorapìs, Marmarole, Tofàne, Pelmo and in the upper part of the Sella Group.

At the end of the Triassic period the large carbonatic platform was submerged and dismembered in various blocks. The typical sedimentation of this tropical bank led to the formation of the Dachstein Limestone and then to Jurassic rocks like the Calcari Grigi (Lias) and the Ammonitico Rosso (Dogger-Malm).

The Createaceous rocks correspond to the Marne del Puez, consisting of marls and marly limestones cropping out in the Northern part of the Dolomites (Gardenaccia, Altipiani Ampezzani).

The most recent and only Tertiary unit in the region, unconformably lying on the Jurassic succession, belongs to the Monte Parei Conglomerate (Lower Miocene). It was probably sedimented in a shallow sea along an articulate coastal line (*Siorpaes*, 1991). It is likely that deposition continued after this time, but the sediments were then eroded during the Alpine chain uplifting.

From a tectonic point of view the Dolomites underwent two main Alpine tectonic phases: the mesoalpine phase during Eocene-Oligocene, when the Dolomites were still below the sea level, and the neoalpine phase which showed the maximum intensity in the Upper Miocene. The dolomitic and igneous rock formed in the Permian and Triassic thus remained

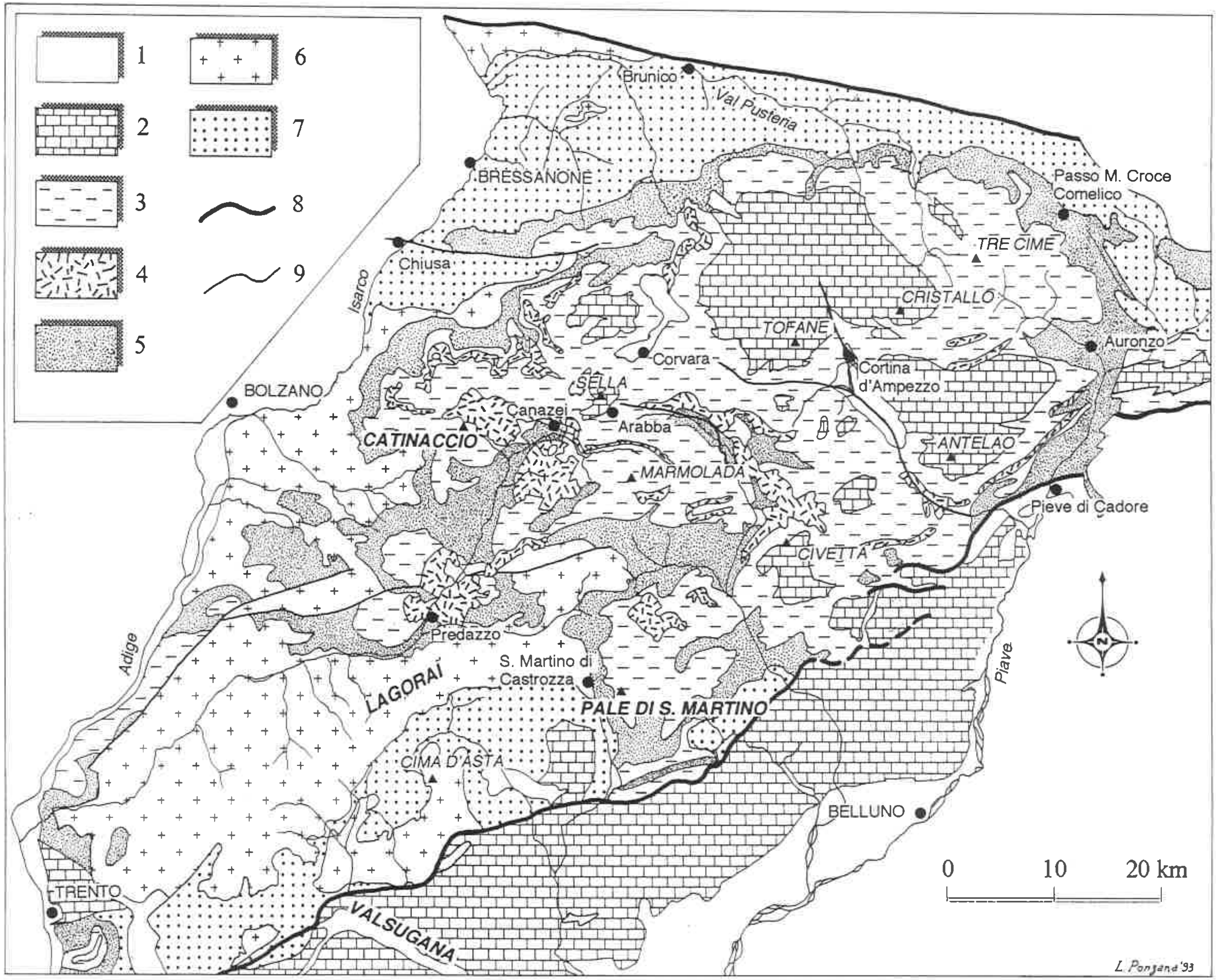

Fig. 4 - Geological schematic map of the Dolomites. Legend:

1) Plio-Quaternary deposits;

2) dolomitic and carbonatic rocks, Norian-Cretaceous (Dolomia Principale, Dachstein Limestone, Calcari Grigi, Ammonitico Rosso);

3) dolomitic and clastic rocks, Carnian (Dolomia Cassiana, San Cassiano Formation, Dürrenstein Dolomite, Raibl Formation);

4) dolomitic, clastic and volcanic rocks, Ladinian (Sciliar Dolomite, Livinallongo Formation, volcano-clastic deposits);

5) clastic rocks, Permian-Lower Anisian (Arenarie di Val Gardena, Bellerophon Formation, Wengen Formation);

6) volcanic rocks, Permian (rhyolites, rhyodacites and dacites);

7) Crystalline Basement, Carboniferous (phyllites, micaschists and paragneisses);

8) main tectonic lineaments;

9) secondary tectonic lineaments.

undisturbed for several million years, buried under enormous piles of marine sediments. During the Tertiary period, because of the collision between the African and European continents, the succession was deformed, dissected and uplifted.

The effects of the mountain building process on the Dolomitic region were not the same everywhere. In fact, the Western Dolomites, due to the underlying thick and rigid Permian volcanic rocks, were uplifted as a quite undeformed block. The Eastern Dolomites instead, not underlain by a rigid substratum, were intensely compressed and folded. As a result in the western sector older rocks like Sciliar Dolomite prevails whilst in the eastern one more recent formations such as Dolomia Principale widely outcrop.

3. STRUCTURAL LANDFORMS

The geomorphological features of the Dolomites are in most cases tightly connected with the geological structure of this sector of the Alpine chain. The tectonic events which have affected the region since the Cretaceous folding, faulting and overthrusting thick piles of sediments, are still clearly legible in the landscape. Furthermore the alternation in space and time of different sedimentation environments, as shown in paragraph 2, together with a recurrent magmatic activity, led to the present vertical and lateral contacts between rocks with different mechanical behaviour, which have been so significant for the evolution of the geomorphological landscape.

Some examples of structure-related landforms will be described below, following the methodological scheme (Fig. 5) proposed by *Panizza* (1982). According to this scheme structural Geomorphology comprises "Morphotectonics", which deals with the relationships between landforms and tectonic movements (as tectonics plays an active rôle, this sector is also defined as "Morphotectodynamics") and "Morphoselection", which takes into account those landforms connected with differential erosion; the latter can be subdivided in "Morphotectostatics" when the relationships between strata attitude (i.e. tectonics with a passive rôle) and landforms are investigated and "Morpholithology" if the physical properties and mechanical behaviour of different kinds of rocks are considered (Fig. 6).

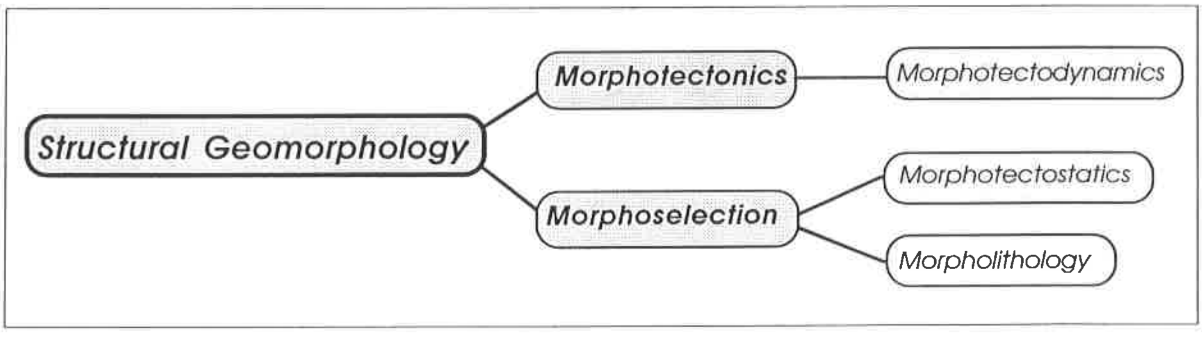

Fig. 5 - Partition of structural Geomorphology (after *Panizza*, 1982; modified).

3.1 Examples of Morphotectodynamics

Cases of Morphtectodynamics may be very frequently observed in the Dolomites; landforms connected with tectonic movements show different dimensions according to the entity and type of movement.

As far as a landform connected with a fold is concerned, the case of Cima Bocche

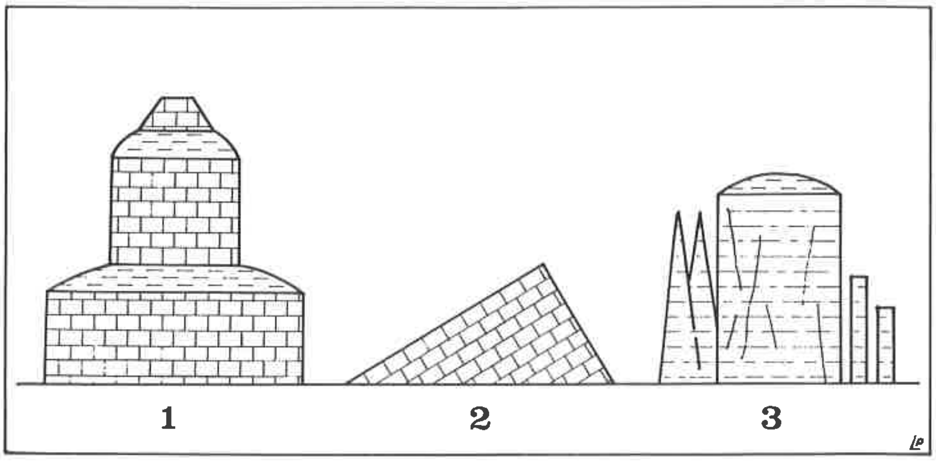

Fig. 6 - Relationships between structure and the most typical shapes of the Dolomite reliefs. Legend: 1) example of Morpholithology due to selective erosion; 2) example of Morphotectostatics due to the attitude of the strata; 3) example of Morphotectodynamics due to the presence tectonic joints (after *Nangeroni*, 1937; modified).

relief, located between S. Pellegrino Pass and Valles Pass (east of Predazzo) should be cited. As a result of the occurrence of an anticline fold affecting the Permian to Anisian formations the topography shows a gentle curvature; since the anticline structure is partially eroded along its axis direction, the phenomenon may be clearly perceived also through a series of natural sections where the stratigraphic sequence outcrops (at Valles Pass and on the near area of Campagnaccia).

As for faults, they have in several cases determined the direction of valleys and river cuts, like in the case of Funès Valley, Tires Valley, upper Cismon Valley and S. Vigilio Valley. In addition, the presence of overthrusts has determined the formation of saddles, like those of Valparola Pass and Falzarego Pass.

Significant evidence of tectonic activity can be found also on a smaller scale; in fact, the development of many deep gorges and troughs is strictly connected with it. This is the case of the trough at the Forcella Piccola of M. Antelào, that is located along the Antelào fault. Displacements on a local scale might have affected only sectors of mountain groups, thus creating spectacular shapes like towers, pinnacles and summits, as in the Latemar Group.

3.2 Examples of Morphoselection

Significant examples of Morphoselection linked both to strata attitude and to lithology are widely represented in the Dolomitic region.

As regards Morphotectostatics, there are evident cases of structural slopes in the Permian volcanic rock plateau located west of Trento (Piattaforma Porfirica Atesina), like the southern slope of Mount Rasciesa in Gardena Valley or the northern slope of the Lagorai Group from Cavalese to Rolle Pass.

Structural slopes can be found also in sedimentary rocks, like in the Marmolada Group (Fig. 7), where the north-facing slope shows a mild inclination, dipping the strata downstream with an angle equal to the slope, and the south-facing slope is very steep because of the dipping upstream of the strata. Furthermore the tabular morphologies of several Dolomitic summits are in most cases related to a sub-horizontal dipping of the strata, as in some well-known mountain groups like Sciliar, Lastoni di Formin, Sella (Fig. 8), Gardenaccia and Alpe Fanes.

The contacts, both lateral and vertical, between rocks showing different mechanical characteristics have allowed a

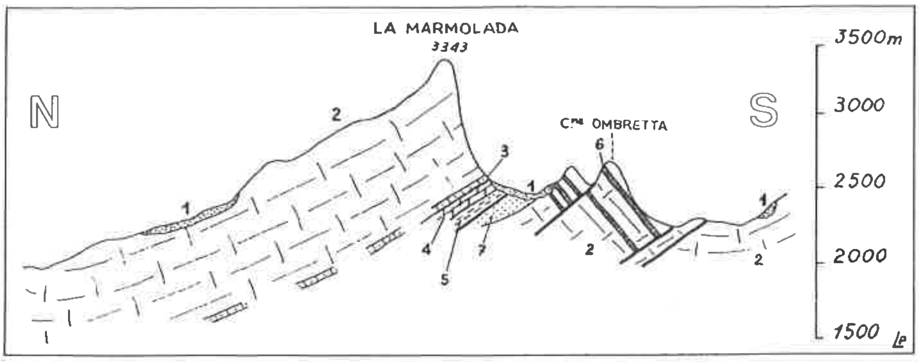

Fig. 7 - N-S geological section of the Marmolada mountain group. Legend: 1) colluvial deposits and scree slopes; 2) Marmolada Limestone; 3) Livinallongo Formation; 4) Contrin Formation; 5) Werfen Formation; 6) volcanic dykes; 7) volcanic rocks (porphyries); 8) tectonic elements (after *Various Authors*, 1977; modified).

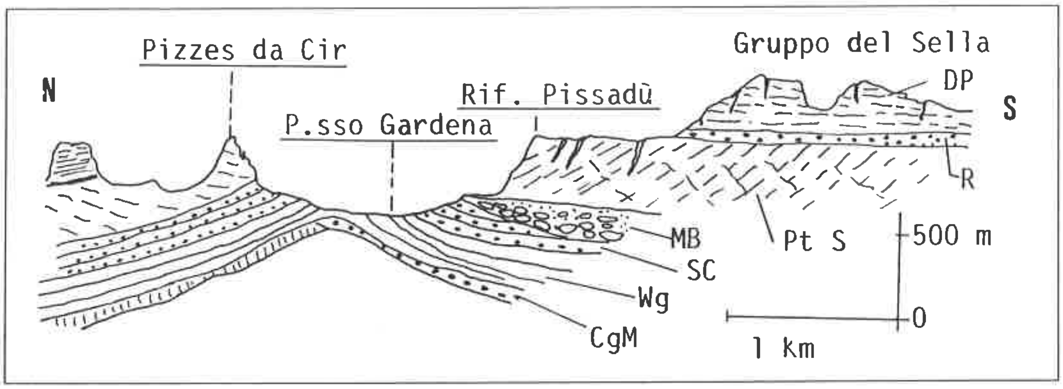

Fig. 8 - N-S geological section of the Gardena Pass and Sella Group. Legend: CgM) Marmolada Conglomerate; Wg) Wengen Formation; SC) San Cassiano Formation; MB) Megabreccias; Pt S) Sella Platform; R) Raibl Formation; DP) Dolomia Principale (after *Carton & Pelfini*, 1988).

selective erosion which modelled steep slopes where the outcropping rocks were more resistant (dolomites, limestones and porphyries) and gentle slopes where weaker rocks (clastic and volcanoclastic rocks) occurred. A typical example is represented by that of the "cengia" of the Sella Group (Fig. 8), where the Raibl Formation interposed between Dolomia Cassiana at the bottom and Dolomia Principale at the top shows a low slope gradient in comparison to the sub-vertical dolomitic walls. However all over the western Dolomites it is possible to observe strong morphological contrasts on slopes where the dolomitic mountain groups overlie clastic formations, like in the area of Cortina d'Ampezzo, where very steep-sided groups like Tofàne, Cristallo, Pomagagnon, Sorapìs and Antelào lie over the highly erodible marls and clays of the San Cassiano Formation.

The location of some Dolomitic passes is also connected with the presence of more easily erodible rocks; this is, for example, the case of the Gardena Pass (Fig. 8), Sella, Pass, Pordoi Pass and Camplongo Pass, which are shaped on clastic rocks weaker than the surrounding dolomites.

On a local scale, Morpholithology examples can be observable where facies variations occur within the same geological formation, as in the Werfen Formation, thus creating horizons characterised by a different degree of erodibility; also the existence of several dykes intruded in sedimentary deposits has given and still gives rise to selective erosion, as may be seen in the Latemar and Marmolada groups.

4. GLACIAL LANDFORMS

As for climate, the landscape appears to be a consequence of both present conditions, which vary and differ depending on altitude and aspect, and of alternating conditions during the most recent geological epochs.

4.1 Pleistocene glacialism

During the Quaternary glaciers repeatedly (at least four times) occupied the Dolomite valleys and have left very evident traces of their presence. However, clear evidence of glacial deposits or erosion landforms older than the last glaciation and datable with certainty remain unknown at present. Only limited outcrops are located in the area of Brunico (*Klebesberg*, 1956) and perhaps along the Piave River in the vicinity of Ponte nelle Alpi (*Penck & Brückner*, 1909). The oldest observable erosion and accumulation landforms are almost exclusively attributable to the Würm glacial period. During this period, ice masses reached relevant heights in all of the Dolomite valleys; only the peaks and some plateaus remained uncovered. The glaciers coming from the large Dolomite groups joined together and created a network of glacial branches intersecting between one valley and another. Some flowed over the present Dolomite passes, which functioned as transfluent saddles at the time: Sella Pass (2.244 m), Pordoi Pass (2.239 m), Gardena Pass (2.121 m), Falzarego Pass (2.105 m) and other minor passes such as Campolongo Pass (1.875 m), Costalunga Pass (1.745 m) and S. Pellegrino Pass (1.918 m). The thickness of the ice in the heart of the Dolomites was substantial, reaching thicknesses greater than 1.500 m. The particular diversity and the distribution of the rocks characterising the Dolomites have also led to the identification of the direction of the glacier movements through the specific analysis not only of the relief morphologies, but also of the distribution of the debris transported along the valleys or from one valley to another. Lateral moraine deposits, attributable to the period of maximum advancement, are found only in the southern sectors of the Dolomites and not in the central or northern valleys. In the latter areas, the glacial surface was above the permanent snow-line and therefore completely contained within the alimentation area. In these same areas, only basal till and scattered material left during the general melting of the ice are attributable to the peak of the Würmian advancement.

The most evident traces linked to glacial morphogenesis that are observable today, are attributable to the subsequent melting phases, which took place intermittently and in a discontinuous manner according to the now well-known outline of the "post-Würmian stages" introduced by *Penk & Brückner* (1909) for the Alpine region. The reduction, followed by the complete disappearance of the glacial masses, exposed various erosion landforms, among which, besides the well known U-shaped valleys, the most frequent are: steps, hanging valleys, sharp rocky crests and cirques. The freshness and permanence of some of these landforms is related to the type of substratum. For this reason, their presence in the Dolomite area is not homogeneous, but follows the distribution of the Ladinian carbonate rocks. Traces of glacial erosion are preserved better in the latter, compared to volcanic rocks. Hanging valleys are particularly evident at the junction of small valleys with the principal valleys: the junction occurs through a step (outlet step). Significant examples of secondary valleys, hanging above the principal valley because they were formed by minor tongues, are present along the slopes of the Fassa Valley at the confluences with the Contrin Valley, Ciampac Valley and Duron Valley. Glacial cirques are scattered almost everywhere, and above all, near the valley heads. The cirques vary from semi-circular to elongated in shape and are isolated or arranged in groups or in a step-like morphology. They often have very steep ridges and supply suitable climatic conditions for the preservation and permanence of snow patches until late summer or even throughout the entire year. Many of them at present contain small cirque glaciers or glacierets. The large number of individual cirques represents an obstacle for a detailed inventory. The flanked glacier cirques present in the Mamarole Group, the isolated and well formed Croda Rossa cirque and the Travignolo cirque, which is deeply carved in the northwestern flank of the Pale di S. Martino Group, are mentioned here only as some examples.

There is also plentiful till deposited by glaciers in the stadial phases. The till is found within many valleys and in the characteristic shapes, but mainly in sequences of frontal ridges which are observable one after the other as far as the individual valley heads. The moraines take on the particular festooned forms, often arranged in sequential rows. They normally present a rounded and not very prominent topographical profile, especially in comparison to the moraines deposited during the Little Ice Age. A soil surface several centimetres thick covers these moraines and depending upon their position, they are colonized by vegetation ranging from Alpine meadows to tall conifers. Their wide distribution throughout the entire Dolomite territory makes it impossible to list their exact locations here. For their identification, see the enclosed geomorphological schematic map (Fig. 9). At times, the study of these morainal remains has led to the explanation of some phenomena such as fluvial dams and the filling of valleys and to the identification of lacustrine basins. Stadial moraines enclose lakes Misurina (Cristallo Group), Carezza (Latemar Group), S. Pellegrino and Lagusel (Marmolada Group), d'Ayal in the vicinity of Cortina d'Ampezzo, Valparola (Tofàne Group), Calaita (Cima d'Asta-Lagorai Group), and almost certainly the Sorapis lake (in the Sorapìs Group) as well. The Braies lake (Croda Rossa Group) has a similar genesis and is enclosed not by a moraine, but by landslide material that originally fell on to a glacier and was then redistributed. The material presenting an overall appearance similar to landslide debris, but distributed over vast areas, should also be mentioned here. It consists of debris from the slopes surrounding the ancient glaciers and which, after the fall, became part of the moraines. Significant examples of this type are found below the Cortina d'Ampezzo basin, east of Campolongo Pass, east of Sassolungo (Città di Pietra) slightly more south than Rolle Pass, in the vicinity of the confluence of the Mis Torrent and the Cordevole Torrent and between the Sorapìs and the Marmarole groups.

4.2 Holocene glacialism

Landforms related to recent or present-day glacier activity are not lacking, even if the existing glaciers in the Dolomite Alps are of limited sizes and they are not as characteristic of these mountains as they are of other Alpine sectors. Their limited development is mainly due to the decrease in the mean altitude of the Alps from west to east, with the resulting reduction of surfaces lying within the altimetric intervals with favourable climatic conditions for the formation and maintenance of glaciers. The Dolomite Alps have a relatively low mean altitude for glaciation. Moreover, although there are numerous peaks in the Dolomites rising over 3.000 m, the high relief energy represents an unfavourable element for glaciation: the steepness of the walls highly

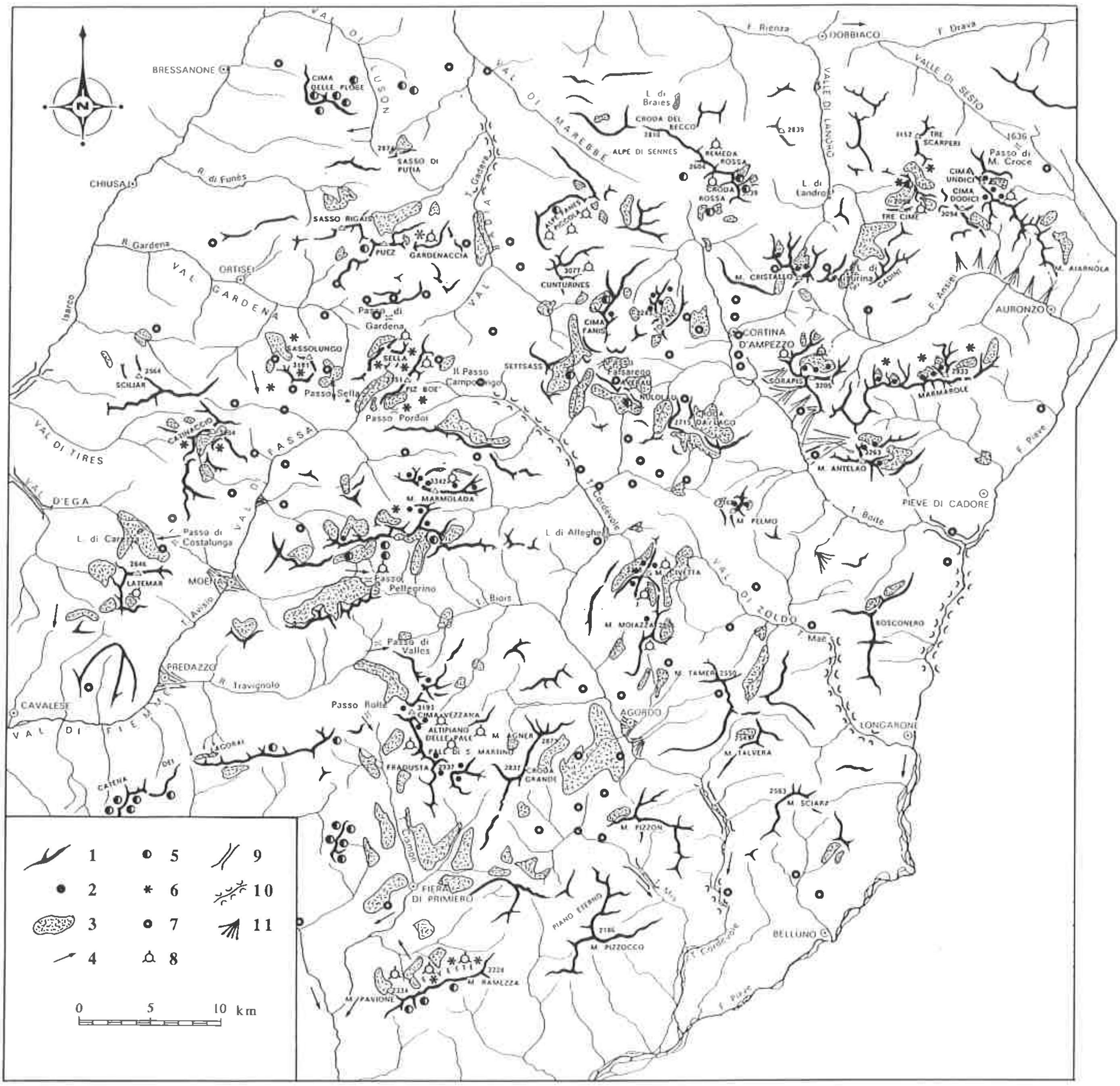

Fig. 9 - Geomorphological schematic map of the Dolomites. Legend: 1) orography; 2) glaciers; 3) main glacial deposits; 4) movement direction of the Pleistocene glaciers; 5) rock glaciers; 6) ice- and snow-related phenomena; 7) main landslides; 8) areas intensely affected by karst phenomena; 9) troughs; 10) deeply eroded fluvial valleys; 11) talus cones and alluvial fans.

reduces the slope surface area lying within altimetric intervals of accumulation. Only some glaciers are located on relatively upward-sloping surfaces suited to receiving glaciers that extend over an entire slope.

The mountain groups which still have ice masses today are listed in the following, from west to east: Popera, Cristallo, Tofàne, Sorapìs, Marmarole, Antelào, Marmolada, Pelmo, Civetta and Pale di S. Martino. Although there were glacierets present at the beginning of the century, the Croda Rossa, Sassolungo and Sella groups have no glaciers at all today. The sizes of the glaciers existing today are small and, with the exception of the Marmolada glacier (about 2.6 km^2; *UNESCO-IAHS*, in press), the most frequent size is between 5 and 30 hectares. These glaciers have a significant rôle for the purposes of paleoclimatic reconstructions: their small size permits them to readily respond to even the slightest changes in temperature and precipitation. Almost in real time, they record climatic variations with fluctuations in volume. The mountain group that has the largest number of glaciated patches is the Marmolada, which also holds the record for the largest glaciated surface area. According to the *UNESCO-IAHS* inventory, there are more than fifty glaciers and glacierets in the Dolomite Alps. Most of the ice masses, with some individual exceptions, are oriented northward and they show an almost symmetrical distribution, with respect to the north. Given the limited sizes of the glaciers in the study area, these data point to an obvious conclusion: their maintenance today is in fact based almost exclusively on the exposure factor alone. Among the glaciers existing at present, only 37% are considered mountain glaciers, whereas most of them (51%) fall within the category of glacierets and the remaining are of uncertain classification. The most frequent types are cirque glaciers (37%), followed by group glaciers (23%), patch glaciers (20%), uncertain (14%) and with simple basin (6%). Alimentation of these glaciers is prevalently from avalanches (51%), while 37% are nourished from a combination of sources, and only 12% receive alimentation from snow precipitation. The most common type of glacier in the Dolomitic region is the cirque glacieret, with a uniform longitudinal profile, fed by avalanches and with uncertain activity of the front. In the vicinity of the front, there are *roches moutonnèes* that are often covered by a veil of debris. Holocene glacial deposits are plentiful and they are modelled in well developed ridges, very often having a sharp profile like knife blades, several dozen metres high, with a marked linear development extending even as far as several hundred metres. They are found near the present glaciers, prevalently in the form of lateral moraines. The frontal section is almost always eroded or however present in residual lobes. The moraines present steep ridges: the external one has the same inclination as the angle of deposition of the debris; the inside ridge is steeper and is an erosion surface where one can observe the characteristic structure of accretion moraines. They are made up of massive diamicton matrix supported, unvegetated, and indicate the position reached by the glaciers at the height of the Little Ice Age around 1850. Inside these ridges, other lower irregular ridges mark several episodes of activity in the present century.

4. PERIGLACIAL LANDFORMS

Processes connected with ice and snow action occurring above the tree-line give rise to a serie of landforms which are very typical of the Dolomites. At these altitudes temperature plays an important rôle, both for its stability below zero degrees centigrades (frozen grounds for a part of the year) and for its variability with passages above and below zero (freeze and thaw cycles).

Talus cones and scree slopes are a very common and sometimes spectacular feature of the region, binding at their base many mountain groups. They are due to frost shattering phenomena which have taken place since the Würmian glaciers' retreat from the valleys; the extension, inclination and granulometry depends very much on the lithology (i.e. physical and mechanical properties) of the alimenting slopes and on the characteristics of the eventual tectonic jointing of the slope itself (*Soldati*, 1988).

Other typical and wide-spread periglacial landforms, often in the vicinity of those mentioned above, are *protalus ramparts*, which are elongated ridges parallel to the slopes and alimented by debris falling from rock walls and sliding on snow patches.

Small scale special landforms due to discontinuous frost action and/or to snow, that is patterned grounds, are locally observable at high altitudes on plateau areas, like on the Sella and Catinaccio groups.

Gelifluction phenomena give also rise to evident morphological features (scars, lobes, small flows etc.) especially on slopes consisting of volcanoclastic and clayey formations. Several cases are observable in the high Cordevole Valley between Arabba and Pordoi Pass.

Avalanche cones, due to the accumulation of debris mixed to snow, are typical in the Dolomites, above all where structural discontinuities affect the slopes; this is the case of slopes characterised by a dense jointing or by volcanic intrusions which have originated morphological discontinuities. Avalanches in some cases may threaten roads, villages, woods and crops thus creating conditions of geomorphological risk.

Rock glaciers represent another interesting landform characteristic of this morphoclimatic environment. They have the traditional shape of flows elevated over the surrounding terrain; the forms held to be active terminate at the front in a high and steep slope. Besides being characteristic in their typical appearance, they also have an important rôle for the purposes of climatic and paleoclimatic reconstructions, as they mark the lower limit of the discontinuous mountain permafrost. In the Dolomites, the lower limit of the active forms is presently located along the mean annual isotherm of -1,5 °C, while that of the inactive forms is situated around 0,3 °C. Approximately 55 rock glaciers have been identified in the Dolomites and only two of them still seem to be active. A comparison with other sectors of the Alpine chain reveals an almost complete absence of active forms, but above all, a low density of forms per km^2. The altitudes of the frontal margins of the active rock glaciers descend to 2.225 m, whereas the inactive ones reach 1.750 m. Forms deriving from sedimentary rocks are quite rare. In fact, although the latter outcrop abundantly in the Dolomites, among all the identified rock glaciers, only 12 are related to those rock types. Volcanic rocks (porphyries), on the other hand, appear to be quite suited to the formation of rock glaciers, as observable in the Lagorai Group (see Fig. 4 and 9). These rock glaciers are prevalently located on slopes and, to a lesser degree, in cirques and in valleys, respectively. The present tongues, which are fairly developed, but not very long, are mostly lowered with the presence of curved furrows and frontal margins that are almost always distinct. One of the largest examples in the entire Italian Alpine chain, just slightly smaller than the largest rock glacier, is situated in the vicinity of the S. Pellegrino Pass in the Marmolada Group. The tongue is 1.250 m long, with several funnel-shaped hollows and numerous curved and irregularly bending furrows which are separated by ridges that are 10 to 12 metres high. Three different phases of activity are evident, one inside the other. The oldest part of the rock glacier appears to be almost entirely covered with tree-growth and presents several hollows that are dozens of metres in diameter. However, the general morphology of the three overlapping phases suggests that the rock glacier is inactive.

5. GRAVITATIONAL LANDFORMS

Gravitational landforms are wide-spread in the Dolomites and represent the effect of mass movements which occurred since the

Würmian Late-glacial period (Fig. 9); at that time huge rock masses, deformed by ice pressure on the slopes and also jointed by ice pressure release, fell on the retreating glaciers which redistributed the debris. Morphological evidence of this is observable in many sites (see 4.1).

The frequency and magnitude of gravitational phenomena is proved to be very high in the last Post-glacial period when slopes, weakened by glaciopressure (*Panizza*, 1973) and no longer sustained by ice masses, were affected by many large scale landslides. In particular, these landslides seem to be concentrated downstream of the confluences of glaciated valleys where glaciopressure might have been more intense, like downstream of the confluence of the T. Costeana and T. Boite valleys (south of Cortina d'Ampezzo) where some large landslides may be seen (*Panizza*, 1973). Then many huge complex landslides occurred in the Lower Holocene, obstructing in some cases the valley floors and thus forming barrier-lakes. Mass movements have been recently dated in the area of Cortina d'Ampezzo, where Quaternary deposits mostly consist of landslides; radiometric datings showed for the Lacedel landslide an age of about 10.000 years before the present, for the Col Drusciè landslide an age of 9.000 years and for some other phenomena ages ranging from 9.000 to 8.000 years (*Panizza*, 1990; *Pasuto et al.*, 1993). Following movements consisted in many cases in reactivations on old landslide sites.

In addition to glaciopressure implications, other significant factors have contributed to the development of mass movements throughout the entire Holocene. First of all the spatial distribution of geological formations (Fig. 4) with different mechanical characteristics must be taken into account. In particular, the occurrence of landslides is particularly high where rigid and resistant rocks (dolomites, limestones etc.) with a fragile behaviour, overlie plastic rocks characterised by a ductile behaviour (marls, clays etc.). Besides the area of Cortina d'Ampezzo, this is the case of the Val Fiorentina (it reaches the T. Cordevole valley from the M. Pelmo) and of the valleys around the Sella Group (Fig. 9). Furthermore, also where the effects of tectonics were more intense, in correspondence of faults or overthrusts, mass movements have been favoured.

Gravitational landforms are also connected with the existence of deep-seated gravitational slope deformations, which have been only recently recognized in the Dolomites and particularly in the area of Cortina d'Ampezzo (*Soldati & Pasuto*, 1991). With respect to morphological evidence, they are generally characterised by the presence of trenches, gulls and uphill-facing scarps in the upper parts of the slopes and bulges in the lower parts (e.g. Tofàne, Lastoni di Formin and Faloria groups). It must be emphasised that deep-seated deformations may represent the initial stage of large scale mass movements whenever the deformation belt develops into a sliding plane. However it has been observed that the presence of these phenomena favours or induces "collateral movements" (rock falls, slides and flows) in the surrounding areas.

6. Karst phenomena

Karst phenomena in the Dolomites are strictly related to structural and morphological conditions. Karst phenomena basically take place in the higher parts of the valleys and are mainly located in the high carbonate massifs (1.200 to 3.000 m), which rest on formations with little or no tendency at all to undergo karst processes. The development of these phenomena is also linked to the variability of the calcium carbonate, magnesium and impurities present in the various rock types. Among the numerous carbonate formations in the Dolomites, only the Marmolada Limestone, Sciliar Dolomite, Dolomia Principale and Calcari Grigi are particularly suited to karstification. The formation containing gypsum of Permian and Triassic age (Bellerophon Formation), outcropping on several slopes and in some valley floors has also undergone karstic processes. However, there are mainly only dolines of small sizes in this formation. They are often alluvial or solution subsidence dolines. A karst landscape sculptured on rocks of this type can be observed, for example, at the S. Pellegrino Pass where there is an outcrop of the Bellerophon Formation. Numerous dolines characterise the slope with a southern exposure and in one of these there is a small lake of karstic origin. From a morphological point of view, the karst phenomena are, however, prevalently common in plateaus, in cirque floors or glacial hanging valley floors, on level summit areas, scarps and ridges. In the first three areas, the prevalent surface forms range from medium to large in size. The most typical karst landforms in the Dolomites are large glaciokarstic depressions, blind valleys, fluviokarstic dry valleys, dolines, glaciokarstic karren, landslide scree heaps with karren and slope karren. The glaciokarstic depressions undoubtedly represent the largest and most characteristic forms (length: 500 to 1500 m; depth: 20 to 60 m). Numerous other minor karst landforms are found within the depressions. The most typical examples of glaciokarstic depressions are found at the Lago Grande di Fùsses, Lago Remeda Rossa di Fosses, Tondi di Sorapìs, Lago Nero on Monte Popera, at Alpe dei Piani, north of Monte Paterno, in the Pale di S. Martino near Forck di Sopra, Buse Alte, Sponde Alte, Buse di Coll'Alto, Riviera Manna and near Piani Eterni, in the Vette and the Feltrine Dolomites. Perennial or temporary lakes often exist inside the depressions.

The most typical example of a blind valley is the Valle del Piano dell'Antelào: it is a hanging valley, on the floor of which there are several sink holes near the terminal step; these sink holes completely drain the existing water that re-emerges through two karst springs about 130 m downslope. The dry valleys prevalently situated in the upland plains are numerous. In general, they are free of surficial hydrography. However, none of them assume specifically typical forms worthy of note. On the other hand, the dolines are numerous: in the Alpe di Fosses, there are dolines with diameters ranging from 50 to 150 m. However, the forms present in the Pale di S. Martino and the Mesules (Sella Group) are of more limited dimensions, thus creating cylindrical pits with diameters ranging from about 1 to 10 m. Very often, the margins of these forms, however, have been modified by periglacial processes that are particularly effective in these environments. Therefore, it is not possible to calculate the exact effects of the karst phenomenon itself. The karren are also very frequent. They occupy wide extensions, mainly on slightly inclined slopes, in highland plains and the floors of the glaciokarstic depressions. They are often complex forms affected by the structural features of the rocks involved, the modalities of glacial erosion and also by karstic morphogenesis: the karren are found on both structural steps and on *roches moutonnèes*. In the first category, one should mention those found in the Civetta Group (Val delle Sasse), the Sorapìs Group (Fond de Rusecco) and the Alpe di Fanes Piccola Group ("Parlamento delle Marmotte"). Splendid examples are still observable on *roches moutonnèes* in the Civetta Group (Valle Moiazza and Val della Moiazzetta), near "I Tondi" in the Sorapìs Group, in the Marmarole Group and near the Alpe di Sennes in the Croda Rossa Group. On the rocks polished by glacier action, other characteristic forms have also been sculptured; they include solution runnels of various types (rectilinear ridge runnels, in small steps, meandering), solution pans (*kamenitza*), solution plains, heel-print karren, grikes several decimetres wide and also many metres long, cavernous karren and interstratified layer pits. There is a remarkable group of hundreds of rectilinear furrows on a ridge made up of a very inclined stratum at Alpes di Fossa (Croda Rossa Group). A similar form is situated in the Civetta Group (Monte Moiazzetta).

Perched blocks are rare in the Dolomites, but they are highly characteristic and always related to the presence of a large erratic block on a calcareous surface. They are visible in the Civetta Group, in the Altipiani Ampezzani and in the floors of several cirques situated in the Alpes Fanes Grande. Pits are also present in the Dolomite mountain groups and several of them are also very evident. However, generally they are not extremely deep. Their presence is often marked by the toponyms *bus*, *busa*, *buche* and *giasère*. Among the most developed of the pits, one should mention the Grotta di Franzei (Roccapietore) with its development of 472 m and depth of 158 m, almost always blocked by ice, the Meandro F2 Alpe di Fosses with its spatial extension of 360 m and depth of 152 m and the Sistema dei Meandri F 10/F 11 Alpes di Fanes.

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