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Tectonics and Tectonogenesis of the Dolomites

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With 6 figures in the text

Southern Alps

The Southern Alps show a structure much simpler than that of the proper Alps; they form a typical «folded belt» which corresponds to a series of folds, thrusted folds and chevron thrusts with axes mostly W–E and plunging mainly toward the South. Folds and faults transversally oriented are also present. There are nappes too, especially in the Grigne Group and in the middle Piave Valley, but they are much less developed than in the other Alpine units.

The southern Alpine structures are separated from the rest of the Alpine structures by a number of large fault lines («Alpine–South Alpine border»), such as the *Tonale Line* (*Insubric Line*), the *Pusteria Line* and the *Drava* (*Drau*) *Line* which, separate two complexes very differently deformed.

The Southern Alps are formed by a schistose-crystalline basement in which phyllites and paragneisses prevail, and by an overlying sequence of sediments which range in age from various periods of the Paleozoic to the Quaternary (see fig. 1 and fig. 2).

The basement («*mesoderma*») and the overlying sedimentary sequence («*epiderma*») show different kinds of tectonic deformation: the «mesoderma» has been deformed by block faulting and composite wedging, (see fig. 5) while the overlying sedimentary sequence exhibits superficial folding (which seconds inactively the basement tectonics) and gravity gliding structures (see fig. 3).

The presence of differential decollements increases the diversity of the different kinds of tectonic deformation, but decollements of regional importance have not been recognised.

Also the various rock complexes which form the overlying sedimentary sequence show different tectonic behaviour depending upon the greater or less plasticity of the rocks (*selective Tectonics*).

There are, however, folds and faults which involve both the schistose-crystalline basement and the overlying sedimentary sequence.

The Southern Alps are transversally divided by the NNE–SSW striking Giudicaria Line and show different widths on the two sides of this Line. The rigidity of the «Atesin porphyric slab», the thickness of which reaches almost two thousand metres, is in part responsible for the larger width of the eastern part where less close folding is observed. It seems probable, however, that this phenomenon is due, even in larger proportion, to other causes which are not well known and which cor-

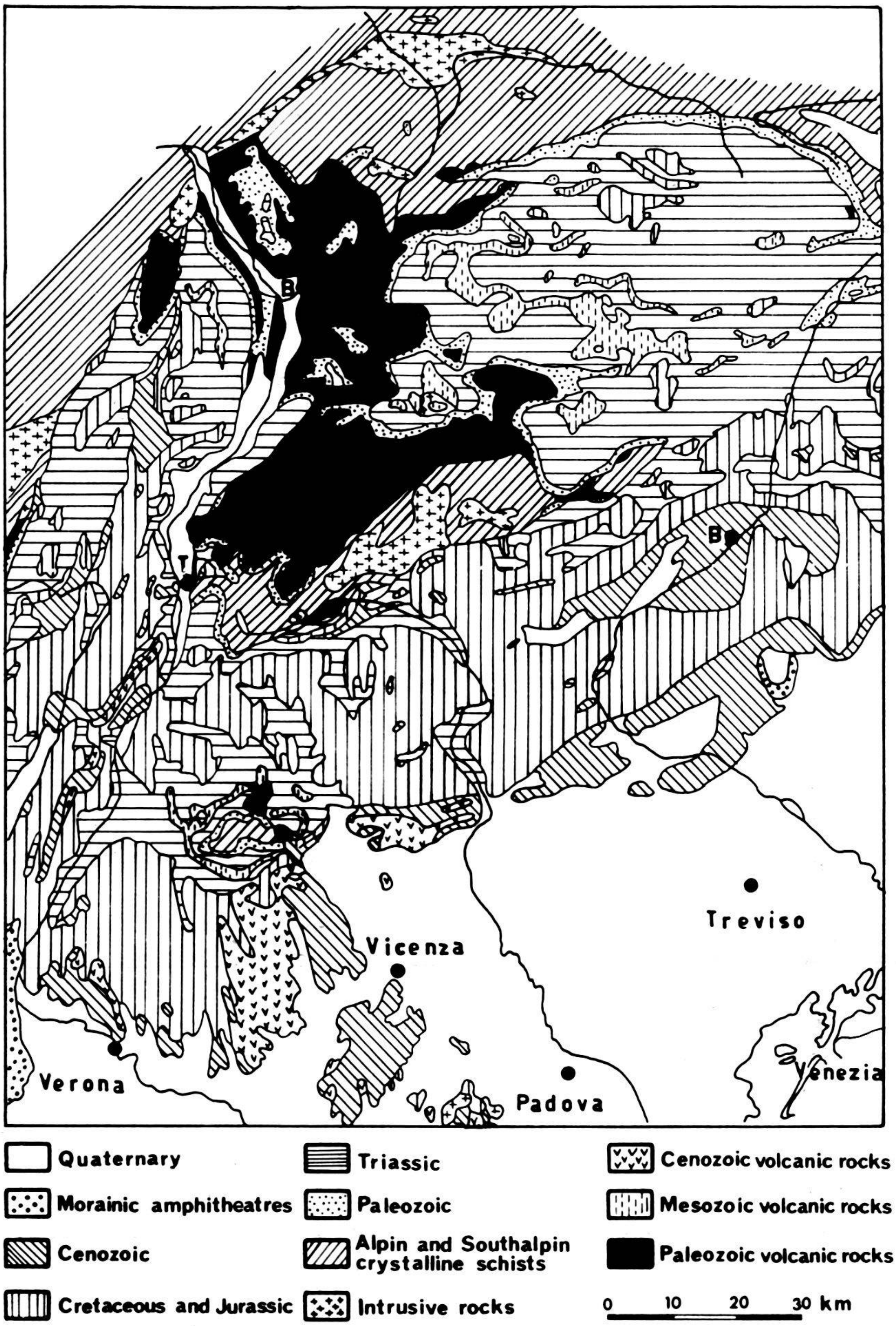

Fig. 1. Schematic geological map (1:1.250.000) of the Dolomites and environs.

respond to deep-seated fractures. Particularly it seems that this fact is due to the presence of a «*structural high*» corresponding to the Western Dolomites (*lato sensu*); this paleostructure, limited eastward and westward by two basins, is called «Atesin platform».

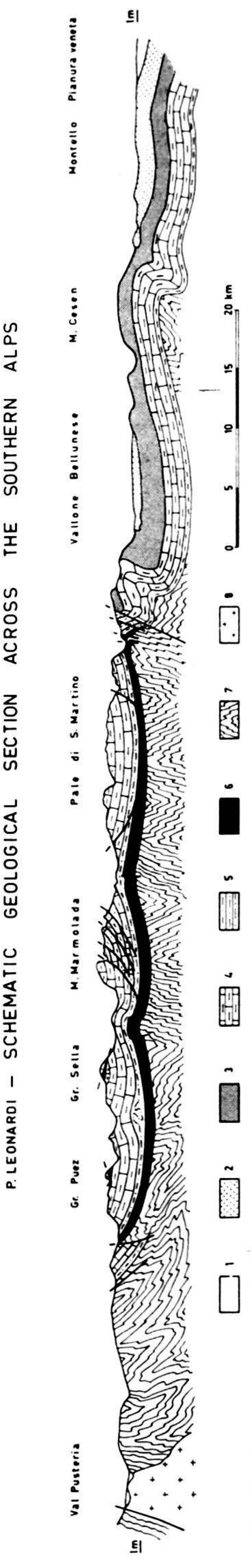

Fig. 2. 1. Quaternary; 2. Tertiary; 3. Jurassic and Cretaceous; 4. Upper and middle Triassic; 5. Werfenian and Permian; 6. Permian porphyric slab; 7. Schystose crystalline basement; 8. Bressanone intrusive massa.

During the tectogenesis of the Dolomites various phases alternatively of compression and relaxation took place. Structures which are due to gravity gliding are well represented, but not all the tectonic structures have been caused by movements of this nature.

General remarks on the tectonics of the Dolomites

The general characteristics of the tectonics of the Southern Alps are valid also for the Dolomitic Region, even if the extreme variability of facies, which characterises the stratigraphy of this region, makes the structures of the overlying sedimentary sequence rather more fragmentary and makes the regional tectonic trends more difficult to delineate.

In the Dolomites too there is a succession of folds and thrusted folds generally oriented W–E or SW–NE or NW–SE and inclined mostly to the S or SE or SSW (see fig. 4). Mainly in the northern part there are exceptions; here some of the structures incline to the North. Generally the synclines are wider and flatter than the anticlines and often the cores of the latter correspond to dolomitic groups which have been left isolated by erosion. The vertical limbs between the folds are often stretched or torn, giving rise to thrusted folds or thrusting slices. The disposition of these tectonic features is frequently the cause of dislocation lines of regional importance like the *Funés* (*Villnöss*) *Line*, the *Tires* (*Tiers*) *Line*, the *Trodena* (*Truden*) *Line*, the *Antelao Line*, the *Valsugana Line*, the *Piave Line*, etc. Subparallel groups of fault lines often correspond to these Lines.

Also in the Dolomites there are folds and faults which involve both the schistosecrystalline basement («*mesoderma*») and the overlying sedimentary sequence («*epiderma*») which includes also the «Atesin porphyric slab». Among these we will mention the Cima d'Asta, Bocche and Lorenzago anticlines, the Travignolo syncline and the Funés (*Villnöss*) Line, Tires (*Tiers*) Line and the Bulla (*Pufles*) Line.

Speaking of the thrusted folds, which are the main characteristic of the tectonics of the Dolomites, we have to note that it is not always easy to recognise the proper thrusted folds, which derive from the stretching of the intermediate limbs of the folds, from the «tear folds» which are the result of fracturing in the schistose-crystalline basement. However, we have to note that the same dislocation might have the character of a fault in the body of a rigid formation while its extension into an overlying or underlying plastic formation might have the form of a thrusted fold or even of a fold (selective tectonics). This fact demonstrates that these different types of dislocations may – at least in several cases – be attributed to an identical tectogenetic phenomenon.

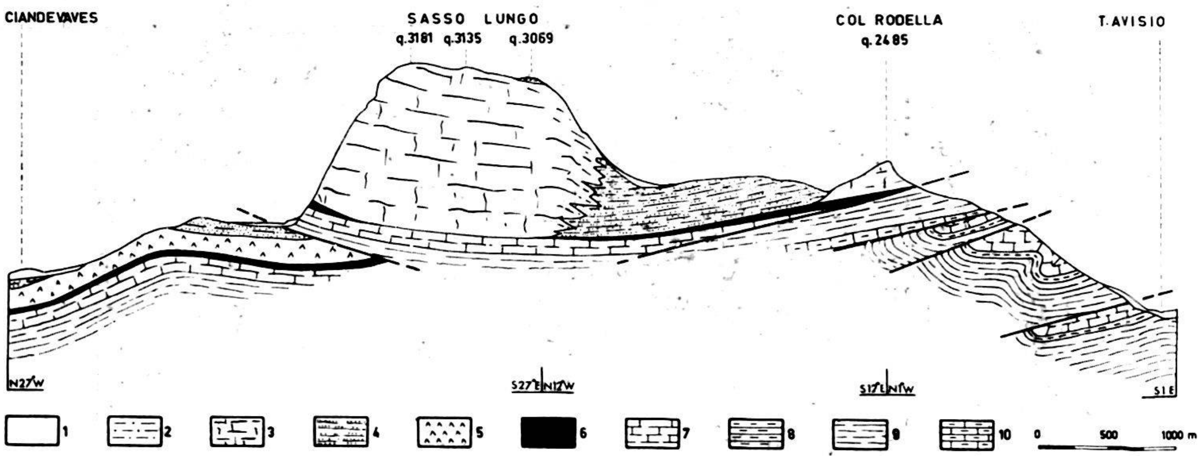

Fig. 3. An example of superficial folding and gravity gliding structures («*tettonica di copertura*»). Geological section across the Sasso Lungo and Col Rodella (Western Dolomites), by P. LEONARDI and E. SOMMAVILLA. 1. Quaternary; 2. Raiblian; 3. Sciliar Dolomit; 4. S. Cassiano and La Valle Strata; 5. Porphyrites, melaphyres and detritic lavas; 6. Livinallongo Strata; 7. Serla Dolomit; 8. Lower Anisian; 9. Werfenian; 10. *Bellerophon* Formation.
Erroneously, it was omitted the Lower Anisian in the left side of the section.

This fact is particularly evident when folds and thrusted folds in the overlying sedimentary sequence correspond to «*composite wedge*» structures of the schistose-crystalline basement and of the «Atesin porphyric slab» (see fig. 5).

The tectonic units of the Dolomites do not show the marked parallelism of the remaining part of the Venetian Alps and Prealps because of the accentuated heteropy of facies. Frequently, in the Dolomites, these tectonic units show a net-type disposition: the meshes are elongated W–E or SW–NE with large development of brachyanticlines and brachysynclines. In connection with this fact, it should be noted also that the heteropy of facies has often been responsible for primary structures (reefs and interposed basins) antecedent to the orogenic folding phenomena. However, this observation does not exclude the possibility that the irregularity of the trends of the tectonic units is partially due also to phenomena of a gravitational nature.

The trend of the net-type disposition of the Dolomitic tectonic units has also given origin to the formation of some characteristic junctions («Scharungen»), such as the *Cadore junction* (LEONARDI, P., 1943), the *Zoldo junction* (LEONARDI, P., 1955) and the *Boite junction*.

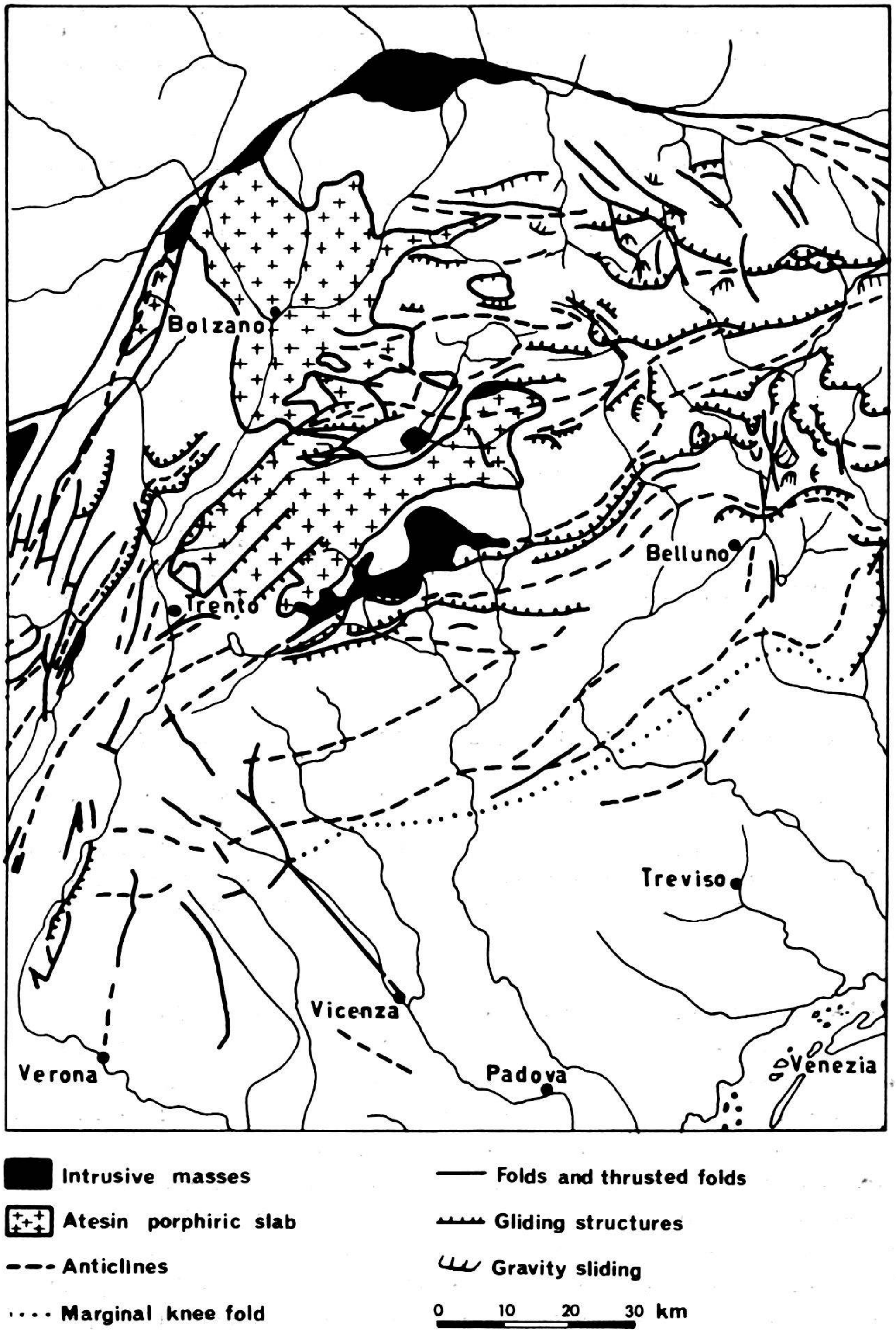

Fig. 4. Tectonic sketch (1:1.250.000) of the Dolomites and environs.

Longitudinal dislocations

We give here a brief list of the longitudinal tectonic units, that is to say of those units which trend W–E or SW–NE, noting that the Dolomitic region might be divided into the following three zones from North to South if we consider the succession of the longitudinal folds and dislocations:

(1) – *Northern zone*, which includes the areas located North of a line which starts from Bolzano, passes through Tires, the saddle between the Col Rodella and the Sassolungo, the Pordoi Pass, the environs of Andraz, the Rocchetta Mountain, the southern slopes of the Marmarole Mountains and reaches Gogna in the Piave Valley. In the western part of this zone the folds often appear to plunge northward.

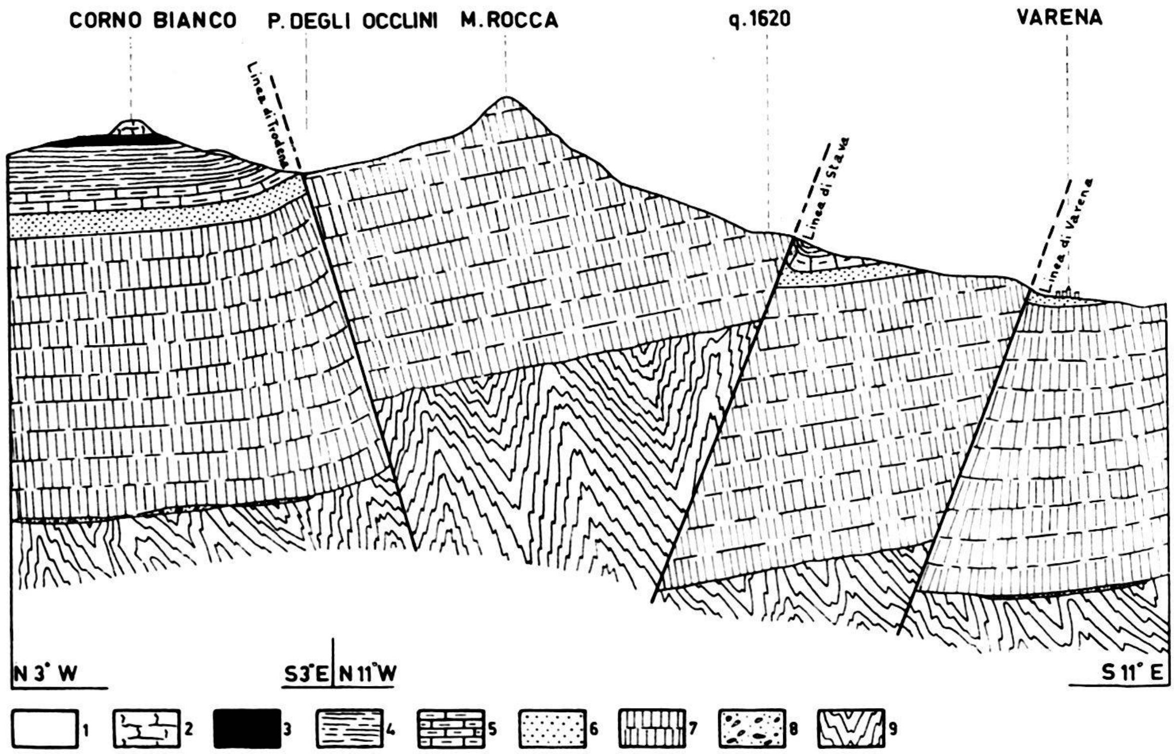

Fig. 5. An example of a block-faulting and composite-wedging structure («*tettonica di fondo*»). Geological section across the Rocca Mt. near Cavalese (Western Dolomites), by P. Leonardi and G. A. Venzo. 1. Quaternary; 2. Serla Dolomit; 3. Lower Anisian; 4. Werfenian; 5. *Bellerophon* Formation; 6. Val Gardena sandstones; 7. Permian porphyric slab; 8. Basal conglomerate («Verrucano Alpino»); 9. Schystose-crystalline basement. Scale 1:65.000

Among the longitudinal tectonic units of this basin we will mention the *Pusteria Anticline*; the *Synclinal Zone*[1]) of *Funés* (*Villnöss*); the *anticlinal Zone of the Bronzoi Pass*; the *Funés Line*, which corresponds to a fracturing of the intermediate limb between the two previous units; the *Syncline of the Alpe di Siusi, Gardenaccia and Altipiani Ampezzani*; the *anticlinal Zone of Plan and Cortina*; the *Syncline of the Sella and Sorapis*.

(2) – *Central zone*, which includes, essentially, the areas of the Fassa Valley located South of the previously cited line, and those of the Cordevole Valley between the above cited line and Alleghe. This second zone, which includes the main

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[1]) We use the term «zone» to indicate an area which during the primary folding corresponded to an anticline or to a syncline, which was more or less complicated and split up by secondary tectonic movements during the secondary orogenic phases.

part of the Dolomites, is very broad West of the Cordevole, while eastward it narrows, becoming at the end a narrow belt which runs along the southern slopes of the Marmarole. This zone is the most complex from a tectonic point of view, and in it there is an overlapping of folds which are often difficult to interpret. These folds are, as a rule, dipping southward.

Among the tectonic units of this area we will mention the *anticlinal zone of the Montalto di Nova and Catinaccio*, which branches eastward in the two anticlines called respectively the *Rodella-Padon anticline* and the *Marmolada anticline*, between which is located the *Syncline of the Buffaure, Fedaia and Fiorentina Valley*; the *synclinal zone of the Costabella.*

(3) – *Southern zone.* This includes all the remaining part of the Dolomitic region, that is to say the largest. In this zone the tectonic trends show a large extension and continuity in the longitudinal direction, and the folds dip mainly to the South. Westward, the tectonic axes bend south-westward and connect with the Giudicaria bundle.

The following «structures» belong to this third area: the *synclinal zone of the Faogna and Latemar;* the *Bocche anticline;* the *syncline of the Travignolo, of the Pale di San Martino and Pelmo;* the *anticlinal zone of the Cima d'Asta and Rite Mountain;* the *Valsugana anticline;* the *Belluno syncline.*

Transverse dislocations

In the Dolomitic region we do not observe a regular intersection of the dislocation lines which belong to two systems with axes more or less normal to each other (Ogilvie Gordon M., 1928). Some of the phenomena which have given origin to this way of reasoning have to be rather attributed to phenomena of culmination and depression of the longitudinal folds (for example, the Bellamonte Line, the Castelir Line, the Paneveggio Line, the Cavalazza Line) or to the existence of those primary structures of sedimentary nature which have been cited previously (for example, the Civetta Line). But it cannot be denied that a certain number of folds and faults with axes more or less normal to the trend of the longitudinal lines previously cited exists.

Among the transverse dislocations we will mention the little folds and thrust silices of the S. Cristina zone in the Gardena Valley, the Perarolo Line, the Val-l'Inferna fault in the Zoldano area, and the series of dislocations which cut sideways the Altipiani Ampezzani with axes directed NW–SE (Val Salata Line, Val di Rudo Line, S. Antonio Pass Line). It is possible that at least some of these transverse tectonic lines, which cut the longitudinal tectonic lines, are to be referred to a rather late distinct orogenic phase.

Miscellaneous faults

In the Dolomites there are several faults, either longitudinal or transverse, which are not related to the primary folding. Most of these faults are reverse faults which indicate compressional phenomena, but normal faults are also present. The most developed among these faults, which have a longitudinal trend, might be referred to a compressional paroxysm subsequent to the primary longitudinal folding. Other faults, either longitudinal or transverse, might be attributed to the balance movements of sections of the blocks in which the Sialic crust of the Dolomitic region was subdivided by the orogenic compressional paroxysm previously cited.

Decollements

In the overlying sedimentary sequence there are several levels at which «differential» decollements occur, but *decollement surfaces of regional importance are never present.*

The «lubricating» levels which more frequently give origin to such phenomena are the *Bellerophon* Formation, the Werfenian, the Lower Anisic and the Livinallongo Strata. The movements connected with the decollements have a strike and dip which apparently differ in the various cases.

Torsion phenomena

The formation of the arch which corresponds to the central part of the «Alpine–South Alpine border» (Giudicaria Line–Pusteria Line) has caused torsion phenomena in the tectonic structures of the Dolomites. These phenomena connect the general direction W–E with that of the Giudicaria Line which trends SSW–NNE. Torsion phenomena are particularly evident at the south-western and north-western limits of the region (Trodena Line, Syncline of Faogna and of the Latemar).

Summit dislocations (Gipfelfaltungen)

Frequently it is possible to observe that in the top part (or summit) of several Dolomitic mountain groups strips of the younger units of the stratigraphic series (Middle Upper–Jurassic and Lower Cretaceous) underlie overthrusted slices of Hauptdolomit, or at least these units show much more complex structures than those of the underlying masses.

Such phenomena have a strictly local character and have to be attributed generally to the gravity tectonics of the overlying sequence.

Volcanotectonics

The particularly complex structures of some areas of the Fassa Valley (Gruppo del Buffaure opposite Pera, Boschi di Borest) and of the Cordevole Valley (left slope between Varda and Campolongo Pass) are due to volcanotectonic phenomena of Triassic age which are connected with eruptions of explosive character. During such eruptions, the lateral pushes of the magmatic gases have given origin to the crushing of the more rigid rock masses and to the gliding of such masses over the more plastic rocks. The demonstration of the volcanic origin of these tectonic complications is given by the fact that these removed masses are more or less totally connected with conglomerates caused by the volcanic explosion and with *Trümmerlaven* (see fig. 6).

Volcanotectonic phenomena of greater importance are recognised in the Predazzo eruptive centre where there are indications of collapse of the rock masses which surrounded the eruptive channel.

Diapirism

In the Dolomitic region certainly there are phenomena of a true diapiric nature, which are due to the bristling up and swelling of originally anidrite formations which might be referred mainly to the *Bellerophon* Formation and to the Raibl Strata. However, these phenomena have a very limited development. Some anticlinal structures at the S. Nicolò Pass in the Fassa Valley and the crumpled Permian layers near S. Martino di Castrozza are the most evident examples of these phenomena.

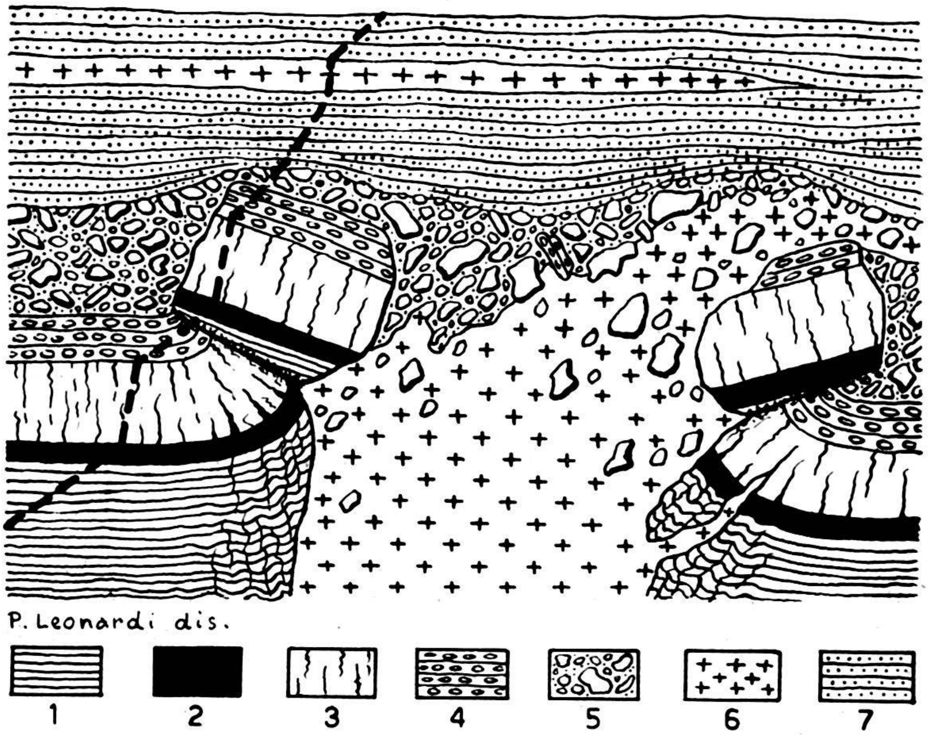

Fig. 6. *An example of volcano-tectonics.* Theoretical interpretation of anomalous positions of the triassic blocks on the left side of the Fassa Valley, in front of Pera village (Col de Pisol). 1. Werfenian; 2. Lower Anisian; 3. Serla Dolomit; 4. Livinallongo Strata; 5. «Explosive» tuffs; 6. Augitic porphyrites, melaphyres and «Trümmerlaven»; 7. Ladino-carnian tuffs. The dashed line on the left shows the slope outline.

There are diapiric, in a broad sense, phenomena about which the geologists have different opinions. According to the recent works of the Utrecht School, a good portion of the tectonic structures of the Dolomitic region are due to diapirism and many of these structures are still developing along the slopes of the valleys which are now being formed (ENGELEN, G. B., 1963).

In particular, the bracysynclinal structures (*saucer-shaped structures*) of some Dolomitic mountain groups are attributed to the foundering of the Dolomitic blocks into their basement formed by plastic rocks which would be pushed outward and upward around the blocks as a result of such a foundering (AGTERBERG, F. P., 1961).

However, even if we grant the idea that phenomena of such a nature have been locally responsible for part of the tectonic structures of the region, we believe, in the first place, that the term «diapirism» is used by the Utrecht School in a too broad sense, and that many of the phenomena under discussion are not of a true diapiric nature. In the second place, we are convinced that the diapiric phenomena are of secondary importance in the tectogenesis of the Dolomites, because they have only contributed to improve structures which were already shaped in their essential lines as a consequence of compressional pushes or gravity gliding.

The same should be said also about the Dolomitic brachysynclines, which, even if they were caused by phenomena of the same nature as those supposed by AGTERBERG, were formed within the limits of preexisting synclines. The complex structures of some zones of the Fassa Valley and of the Cordevole Valley previously cited (Buffaure, Varda-Campolongo) are fundamentally due to volcanotectonic phenomena, even if they might have been further complicated by diapiric, in a broad sense, phenomena.

Relationships between tectogenesis and magmatic intrusions

According to AGTERBERG, F. P. (1961) the uplift of the schistose-crystalline masses outcropping to the North and South of the Dolomitic region and the consequent foundering of the region are due to the rise of the intrusive masses of Bressanone and Cima d'Asta.

We are not able to visualise how the magmatic intrusion in discussion might have influenced so radically the tectonics of the Southern Alps. Particularly in regard to the Bressanone granite, its evident relationships with the large fracture of the Alpine–South Alpine border clearly show its connection with orogenic phenomena of much greater importance than that of the local phenomena mentioned by AGTERBERG.

Moreover, in regard to the case of Cima d'Asta, the fact that the granite intrusion in question appears to be of Hercynian age, according to the researches carried on in the laboratories of nuclear geology of Pisa (FERRARA, G., HIRT, B., LEONARDI, P., & LONGINELLI, A., 1962), is certainly not in favour of AGTERBERG's hypothesis.

Compressional or gravitational tectogenesis

We have valid arguments supporting the hypothesis that the tectonics of the Dolomites are due mostly to compressional phenomena and not solely to gravity gliding.

We have already mentioned that many Dolomitic structures (folds and faults) involve not only the «epiderma» (overlying sequence) but also the «mesoderma» (schistose-crystalline basement) and they seem to be due to a primary folding phase of compression.

Particularly, good arguments in favour of the compressional phenomena are: (a) the character of *reverse* faults or thrusted folds which show several fractures, which can be referred either to the previously mentioned primary folding phase or to a successive orogenic paroxysm; (b) the cleavage planes which are parallel to the axial planes of the folds and to the planes of the faults; (c) the existence of folds and faults trending northwards, especially in the northern part of the Dolomitic region.

However, there are structures which show more or less clearly an origin due to gravity gliding. Besides the well known summit dislocations (*Gipfelfaltungen*) there are several gliding structures and true nappes (especially in the middle Piave Valley) or a series of epidermic «cascade» folds which probably correspond to gravity gliding. Some normal faults, which are present on the back of the epidermic structures previously cited, are also good indications of gravity phenomena.

It does not appear, however, that the structures of this second group make it necessary to accept an *integral* gravity tectonics theory, in that all these phenomena might be attributed to local gliding, even though of remarkable importance, which is in agreement with the idea of a primary compressional tectogenesis.

All that we have observed in the Dolomitic region during more than thirty years of research seems to confirm what J. Aubouin says in general about the Mediterranean orogene: «some fundamental movements result from a compression at the level of the crust» while «some subordered movements result from the gliding of the overthrusting masses» (1961, p. 42); and what De Sitter says in general about the mountain chains: «*...there can be no doubt that the lateral compression is primary, the gliding secondary*».

Considering the actual state of our knowledge, however, it does not seem sensible to us to exclude *a priori* the possibility that also the undoubted compressional phenomena we have cited belong to a more general process of gravity tectonics: nevertheless it does not appear that this process can be demonstrated on the basis of the data which can be observed in the field.

Tectogenetic processes

We believe that we can state that the actual tectonic structures of the Dolomitic region are due to the concourse of the following distinct processes:

(a) primary longitudinal folding due at least in the larger part to compressional phenomena; several tectonic units among the larger ones have to be attributed to this primary phase; deep seated folds with large radius which involve both the schistose-crystalline basement («mesoderma») and the overlying sequence («epiderma»);

(b) gravity gliding on the sloping surfaces caused by the primary folding: smaller and more complex dislocations of the overlying sequence («epiderma») are due to this gliding;

(c) primary longitudinal fracturing deriving from compressional paroxysms which caused the subdivision in blocks of both the schistose-crystalline basement and of the overlying sequence, and the formation of fault lines of regional importance;

(d) secondary fracturing, both longitudinal and transverse, due to different causes, of the masses which had been previously moved by both compression and gravity gliding;

(e) transverse folding, which might be attributed to one or more tectonic compressional phases with pushes acting in a direction normal to that of the primary folding or to components of the forces which caused the longitudinal dislocations;

(f) diapiric, in a restricted sense, movements and swelling which are connected to gypsum-bearing formations;

(g) diapiric, in a broad sense, movements determined either by the weight of the isolated rigid rock blocks which lie on plastic rocks, or by the foundering of the anticlinal domes or by the erosion of the valleys.

We should note that these processes are considered «distinct» only because they can be attributed to different causes, but they are more or less closely associated in regard to their accomplishment and also they might have taken place partly contemporaneously during the orogenic development. We have also to note that in the Dolomites, within the limits of the «epiderma», the superficial folding (which seconds inactively the basement tectonics) and the gravity gliding structures are associated and that it is not always easy to separate precisely these «epidermic» structures.

Chronologic succession of the tectogenetic phenomena

The tectogenesis of the Dolomites corresponds to several successive phases, some of which (involving almost exclusively the schistose-crystalline basement and the Paleozoic «Atesin porphyric slab») go back to the Hercynian orogeny and its late phases, while most of these phases are part of the Alpine orogeny which includes some of the Mesozoic preliminary phases.

While some of these phases are easy enough to recognise, others are not. In any case, we should keep in mind that some of these phases, even if they are distinct in relation to the nature of the phenomena, are more or less partially contemporary, that is to say that some might have begun while earlier ones were already developing.

We propose the following chronologic succession as a premise and with the due reservations:

HERCYNIAN OROGENY

Late phases (*Saalic phase*) – various faults which involve the schistose-crystalline basement and the «Atesin porphyric slab».

TRIASSIC OROGENIC PHASES – orogenic movements proved by stratigraphic lacunae and unconformities of Lower and Middle Triassic; structures N–S directed.

PREALPIDIC OROGENIC PHASES	
(a) Paleocimmeric phase	– unconformities and breaks of Rhaetic and Lower Liassic ages.
(b) Cimmeric phase	– this phase was not particularly sensible in our region (see instead Julian Alps); we have only diastems and hard-grounds in Dogger and Malm sequences
(c) Pre-Gosau phase (Austrian)	– conglomerates and sandstones of Upper Cretaceous age resting unconformably on the Liassic sequence. Growth of local structures (Western Trentino, Cimolais, etc.).
ALPIDIC OROGENY, in a restricted sense	
(a) Early orogenic phases (Upper Cretaceous-Eocene)	
Phase of primary compression	– accentuation of a general preexisting folding. Flysch deposition in some lateral troughs.
(b) Main insubric phase	
(1) Main compressional paroxysm (Lower Oligocene)	– further accentuation of preexisting folds; formation of the main fracture-lines (Valsugana Line, Giudicaria Line, Funès Line, Tires Line, etc.).
(2) Phase of relaxation (Middle Oligocene–Middle Miocene)	– formation of normal faults.
(c) Late insubric phases	
(1) Late compressional paroxysm (Upper Miocene)	– renewal of the main fracture-lines (Valsugana line, Giudicaria line, etc.).
(2) Phase of relaxation (Lower and Middle Pliocene)	– formation of normal faults; renewal of some compression faults with inversion of the movement direction.
(3) Final phase of compression (Uppermost Pliocene-Quaternary)	– formation of the «Foothill Line» (*Linea pedemontana*); uplift of the neogenic foothill rocks (including Pliocene).

Gravity sliding phenomena were present in almost all the various phases but they probably were more frequent in the various phases of relaxation.

Conclusion

Considering the actual state of our knowledge, the problem of the causes of the tectogenesis of the Dolomites still remains unsolved.

We have seen that in the Dolomitic region there are structures which can be attributed without doubt to gravity tectonics. But it is also certain that there are structures which are due to phenomena of compression. Might also the latter be referred to general gravity tectonics as in accord with the ideas expressed in its most integral terms by the Utrecht School? Or do the two types of structure correspond to two distinct tectogenetic processes, a primary compressional and a secondary gravitational?

On the basis of the facts we have observed, we would lean towards this second interpretation. But we think that at the moment we do not have enough knowledge to settle the controversy which obviously affects not only the Dolomite region but the whole Mediterranean orogene and even all the «folded belts».

We believe also that none of the theories proposed up to now, not even the hypothesis of the subcrustal currents or, particularly, RITTMAN's theory, which we prefer, is safe from criticisms and difficulties. In our opinion all these ideas have the value of workable hypotheses, very useful for the progress of research, but are insufficient to give us satisfying reasons for the phenomena which the field geologist can observe on the surface.

We would hope that a more accurate and complete study of the Dolomite region, supported by the most modern methods of research, and the frank and objective discussion of the known facts will give us, in the near future, a more satisfying knowledge of the alpine tectogenesis and in particular of the complex phenomena which have given the actual tectonic structures to the Dolomites.