Z. Geomorph. N.F.	Suppl.-Bd. 109	41–62	Berlin · Stuttgart	Oktober 1998

The Montello Plateau

Karst evolution of an alpine neotectonic morphostructure*

FRANCESCO FERRARESE, UGO SAURO and CHRISTIAN TONELLO, Padova

with 15 figures and 4 tables

(Supplement: Geomorphological map)

Summary. In the Southern Alps the Montello ridge is one of the most singular sub-alpine groups, a kind of low plateau comparable to a turtleback.

This morphostructure, constituted by a conglomerate rock unit of messinian age formed mostly by limestone pebbles bound by a carbonatic cement, is the expression of the up-arching by compressional shortening of a tectonic wedge.

The gradual upsurge of the morphostructure above the plain has exposed it to the erosional processes first of all by the rivers and secondarily by karst denudation.

On the base of a computer aided analysis the main morphological sub-units are distinguished and analysed. Some of these sub-units present characters of wide rock cut terraces. The characters of the dolines, consisting in a large population of more than 2000 forms, allow to evaluate the relative age of the surfaces of the correspondent sub-units.

The sub-unites of the hill can be divided into two groups: the north-west group and the south-east group. The dolines of the NE group are more numerous and smaller than those of the SE group.

In the NW group a step of seven rock cut terraces is easily recognisable where the volumetric developments of the dolines are well correlated with the relative altitudes of the same terraces.

In the morphostructure the following types of dolines have been distinguished: a) plateau dolines, b) terrace-scarp dolines, c) terrace-slope dolines. The plateau dolines are those of the summit plateau of the hill; the terrace-scarp dolines are influenced by the scarps of the terraces; the terrace-slope dolines are similar to the plateau dolines but are settled on the "slopes" of the terraces determined by the anticline bending of the morphostructure.

In the morphodinamical context of the Montello hill the dolines begun to develop as large and shallow forms and their development in the vertical dimension (depth) is controlled by the time, by the character of the basin (the terrace-scarp dolines are in general deeper than the plateau and terrace-slope dolines), and by the geological structure (the dolines along the anticline axis are deeper than those to the north and to the south of it).

With reference with the general evolution of the morphostructure it is possible to recognise the older age of the central and eastern surfaces. This could be related with a former "emersion" from the alluvial plain of this part of the morphostructure and perhaps with a westward migration of the up-bulging of the hill.

---

* (Research carried out with contributions of the Ministery of University and of Scientific Research (MURST 40 % and 60 %) and of National Council of Research (Committee 013): Evoluzione, dinamica e cambiamenti ambientali di geo-ecosistemi carsici prealpini: interconnessioni fra processi naturali e modificazioni antropiche – confronti con altri geo-ecosistemi carsici)

0044-2798/98/0109-0041 $ 5.50

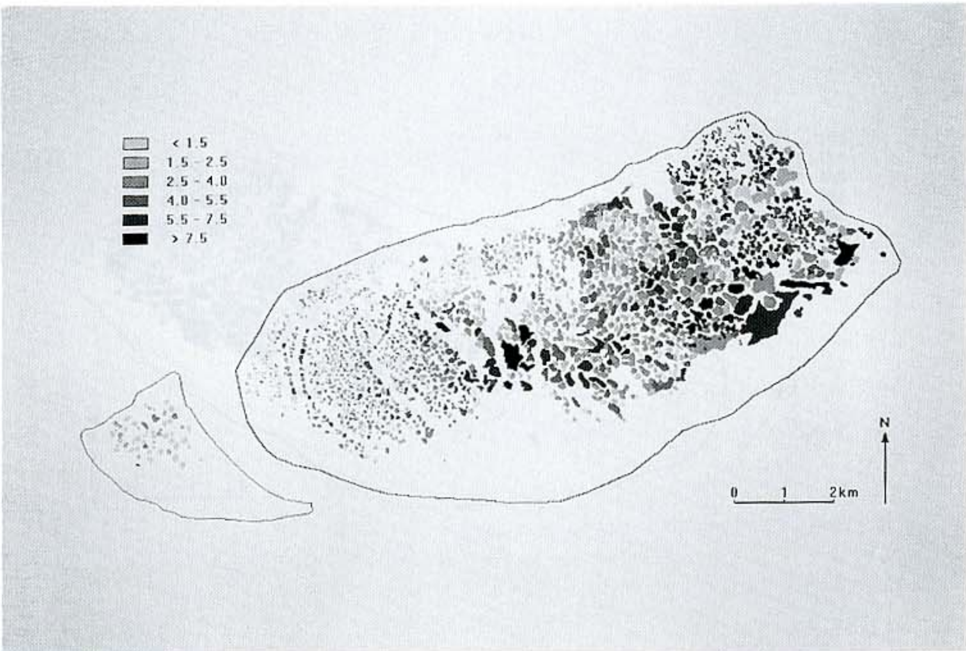


Fig. 6. Map of volumetric depths (HVOL) of dolines expressed in metres. Deepest dolines are generally clustered.

variable ADOL, VOLU, DIDE, HVOL, ID, relative to morphometric aspect of 2125 dolines, have supplied interesting results for a comparison among the different sub-units.

The areal values of the dolines (ADOL) have been distinguished in six classes (Fig. 4). It is possible to observe the clear distinction of the western terraces mostly under 6000 m^2. Here the largest dolines are lined up following the base of the slope ("scarp effect").

The subsummit zone presents high values; starting from it the areal value decreases uniformly in almost all directions. Low areal values are recognizable in the northern sector of the hill, especially in the NE zone. The central zone of hill, where a great part of the dolines are coalescent, shows a great range of value. Here a line up of large dolines into the NW-SE direction is easy to be seen. The north-east sector presents forms comparable to those of the western terraces. As the ideal diameter (DIDE) is directly derived from the areas, it is closely related to these.

The distribution of the volumes (VOLU) (Fig. 5) shows the same trend as the areas evidencing a strong correlation between the two variables. The "scarp effect" is pointed out by the volumes, above all in the fourth and fifth terraces. Finally, in the whole hill a growing trend of the volumes in a NW-SE direction is evident.

Volumetric depths values are also interesting (HVOL) (Fig. 6). A common increase from west to east is clear: least values that share the second terrace with a group of dolines of the central-northern zone, and the central zone that stands for a large range of values. The values of the NE sector are generally high, but those of the narrow band in the south of the same section are rather low.

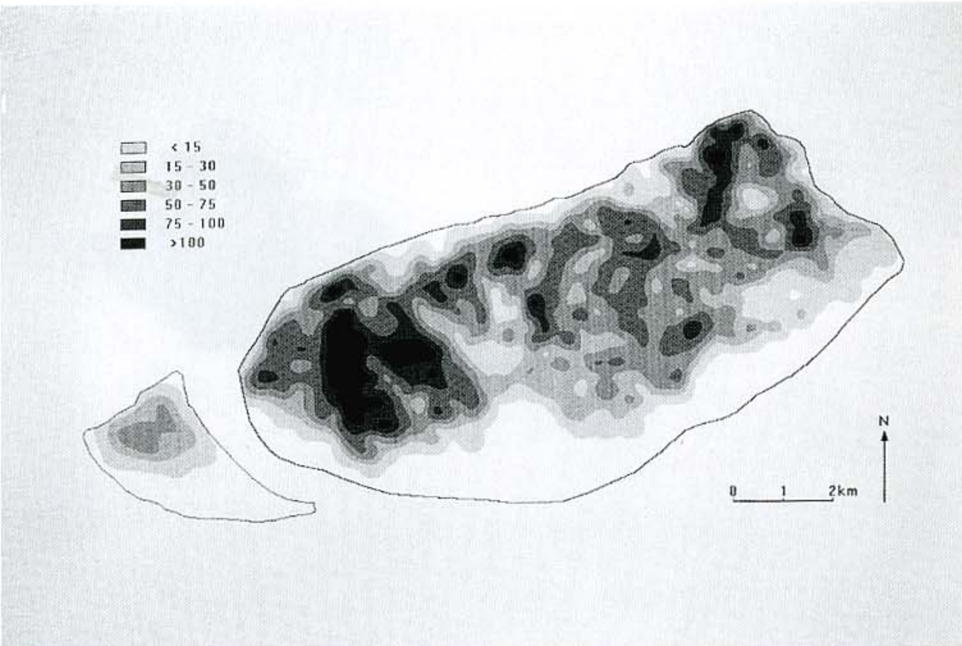


Fig. 7. Map of density of dolines (DDEN; n° dol./km²). The density is higher where dolines are smaller (see Fig. 3).

On the basis of the parameters of morphokarst units VCAR, APER and DDEN it is now possible to restore significant pictures for the distinction of the sub-units themselves [2]. The density of the dolines (DDEN) (Fig. 7) shows a significant distribution with the great values on the NE band of the hill and on the western ledges. The general tendency, however, is to show a higher density in the north of the anticline axis. The behaviour turns to be the opposite of the one of VCAR (Fig. 8), which is generally higher in the south of the anticline axis. A progressive increase of the volumes per area in the W-E direction, with a relative maximum in correspondence of the subsummit zone in the east of the topographic culmination is also noticeable.

The percentage of the area covered by dolines (APER) (Fig. 9) gives prominence to the central-eastern zone with clearly high values (more than 80%). Here dolines are par-

[2] These three parameters were calculated on a network of squares (250 m per side). The obtained values were tractated with a filter "low pass" that produces the media of the internal values of the filter area. The choice of the dimensions of the sampling area is based on an empiric method: we used sufficiently small areas to obtain surfaces on good detail, but not so small to emphasize too much the value of the parameter inside the sample. After some proofs, the square of 250 m per side proved the most suitable for this kind of rapresentation, allowing to express discreet homogeneity in the distribuction of the values, without, for this reason, going to the detriment of the geographic localization.

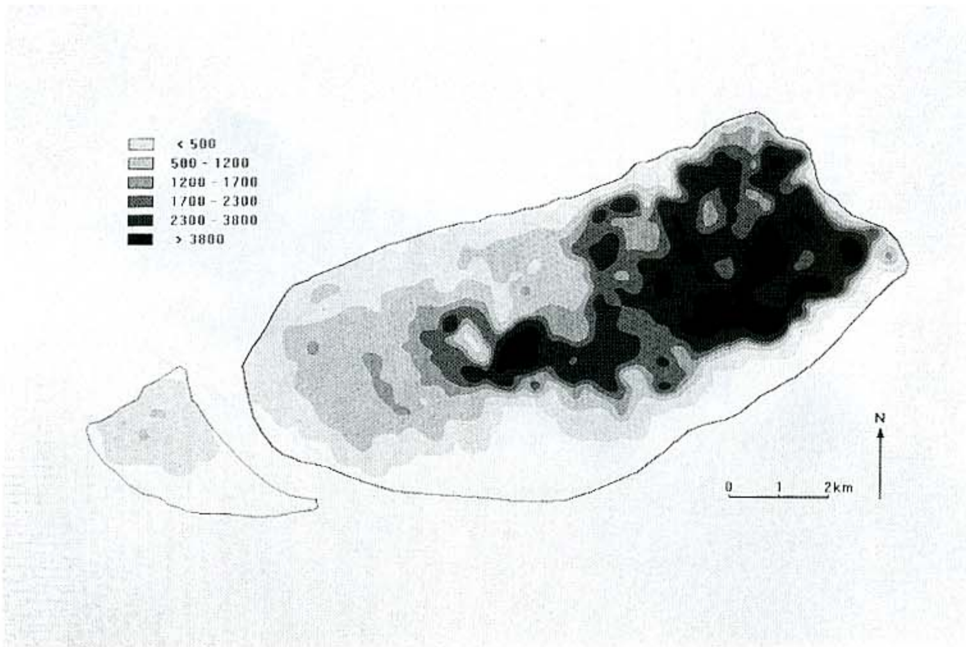


Fig. 8. Map of index of karst relief (VCAR; $m^3/km^2 \times 1000$). It is possible to divide Montello and Montebelluna hill in two zones: the NW part and the SE one. Notice the scarp effect along the inner side of 6th terrace.

tially coalescent trending to the fusion of more units in a single complex form ("dolina multipla", by TONIOLO, 1907).

The reading of these trends and of the previous digital-images allow the distinction of homogeneous zones from the morphometric point of view. Therefore the whole population has been divided in subsets on which a statistical analysis per samples has been performed (Fig. 10). Particularly interesting the zone of western terraces, where it is possible to sketch a diachronic series of dolines evolution.

6 *Analysis and comparison of the located sub-populations*

The sub-unites of the hill can be divided into two groups: the north-west group of Montello – with the hill in Montebelluna (NW group) and the south-east group (SE group). The former group has typical morphological features as the presence of extended subhorizontal surfaces and a narrow range of sizes of dolines. On the contrary, the SE group is generally marked by bigger dolines, even if it shows a wider range of morphometric values. The main sub-units inside the groups are: the seven western terraces and the northern ones in the NW group; the subsummit, the middle south and the south east zones in the SE group.

The SE group of hill has an extension of 33,3 km^2, on which there are 881 karst depressions that means a total density of 26,45 dolines per km^2.

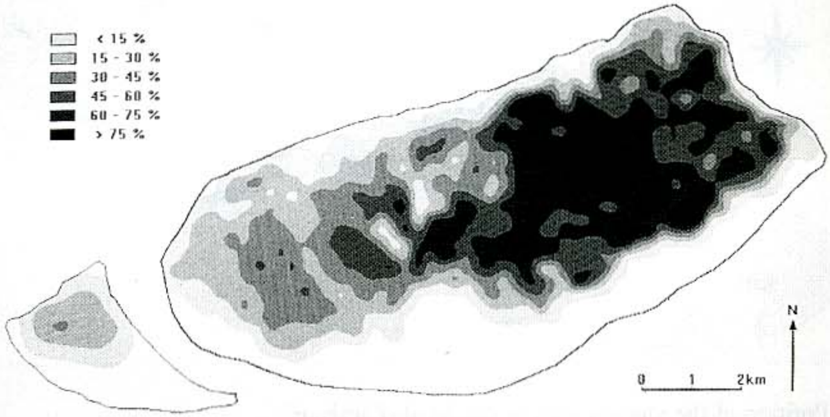


Fig. 9. Map of percentage of area (APER) occupied by dolines. Very closed dolines distinguish the middle-east part of Montello.

The NW group covers an area of 27,47 km^2, where 1189 depressions exist, corresponding to a density of 43,28 dolines per km^2.

Although they show a range of similar altimetric values, the two groups differ from the average altitude: 192 m in the SE and 227 in the NW (Table 1).

The NW group

The dolines of this group are more numerous and smaller than those of the SE group. Between area and volume there is a high correlation: the mean value of volume is four times as big as the areal value, against the six times of the SE group (Fig. 11). The volumetric depth (HVOL) turns out to be lightly greater, which affects the index of development (ID: 38,9 against 45,2 of the SE group) (Table 2).

Table 1. Parameters of a morphokarst unit in the three main zones of the studied area. Notice the trend of APER and VCAR.

	KARE	KMAX	KMIN	KAVE	DNUM	DDEN	APER	VCAR
Montebelluna hill	5.6	195.0	117.5	159.5	55.0	9.7	8.3	110809
Montello NW	27.4	369.0	90.0	227.0	1189.0	43.3	23.7	708673
Montello SE	33.3	365.0	76.8	192.0	881.0	26.5	51.7	2486863

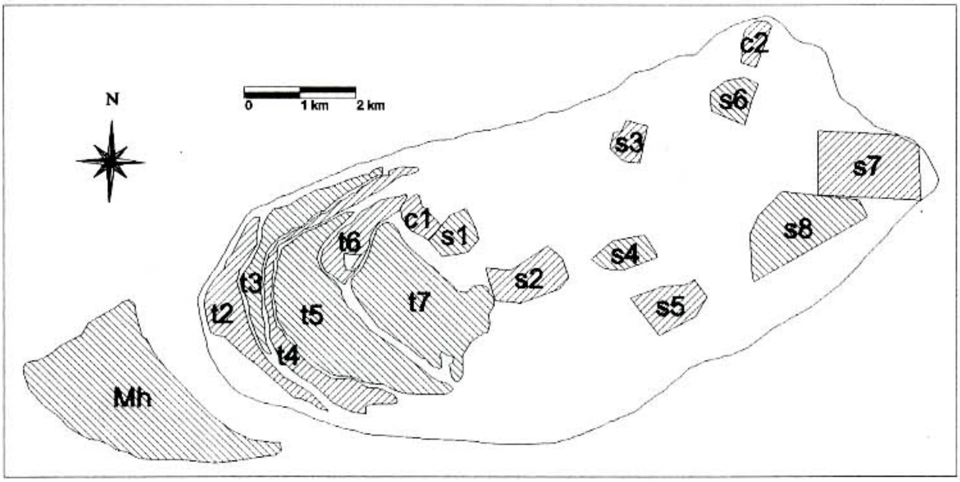


Fig. 10. Position of the samples used in the detailed analysis.

The analysis of this NW group is based on nine samples: the hill in Montebelluna, the western terraces (from the second to the seventh), a sublevel belt located just to the north of the highest point of the hill and the north-west belt of the hill (Table 3).

The surfaces of the western terraces (t2-t7) present growing ages from the bottom upwards. That's why in the first terrace the karst process had little time to perform, so that the development of the karst forms turn out to be scarce while in the highest terrace the karst relief is more highly developed.

The VCAR values point out that the karst relief is more evolved on the oldest terraces according to their relative altitudes. However, we can unexpectedly notice how the density of dolines decreases on the highest surfaces (t6 and t7). Even the 4th terrace (t4) has an anomalous density, which is definitely low compared to the others: the dolines are few but big, as is also shown by the high values of planimetric extension, depth and volume (a feature probably due to the "scarp effect").

APER values of the 4th and 6th terraces (t4, t6) differ from the general tendency to increase, according to the age of terraces. In these two surfaces the dolines are developed mostly in depth, as is shown by the course of the altimetric parameters and the index ID.

Table 2. Mean and standard deviation of the five parameters calculated in the whole population and in the two divided zones.

	ADOL	VOLU	DIDE	HVOL	ID
Tot.					
mean	9935.32	36995.33	98.49	2.70	45.17
st. dev.	18698.67	119705.08	54.32	1.64	33.18
NW					
mean	5351.28	15542.35	77.43	2.48	38.99
st. dev.	4708.92	22645.35	28.62	1.34	32.06
SE					
mean	17683.50	73256.28	134.09	3.08	55.60
st. dev.	28940.84	188743.70	67.40	2.00	32.44

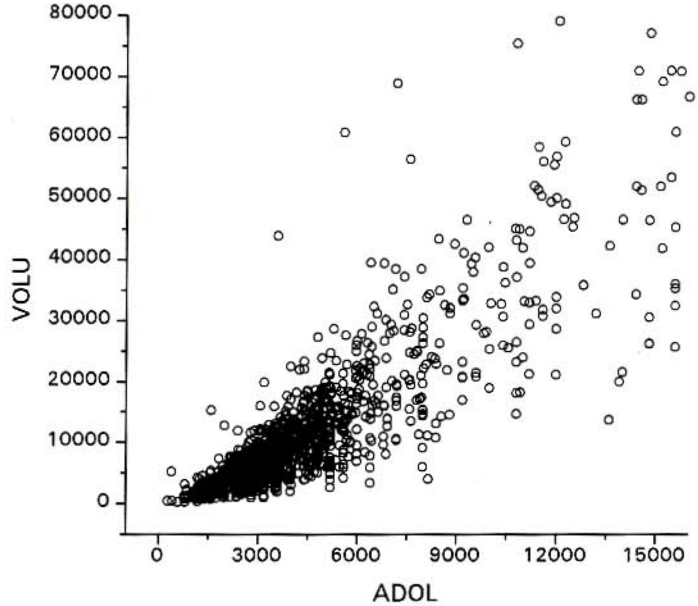


Fig. 11. Distribution of area and volume in the NW group. 34 points are skipped because out of range. Linear regression between the two variables is: VOLU = −6788.9 + 4.1633 × ADOL. R = 0.867.

The high value of VOL in the 7th terrace (t7) and the tendential prevalence of development in depth according to the increase of age are also remarkable (course of index ID).

On the contrary, in the 2nd terrace (t2) HAVE and HVOL are lower compared to the general trend. This was probably caused by the man made changes aiming to fill up these shallow depressions in order to improve agricultural use. But we can't exclude that these dolines - in their early evolution phases - tend to extend more in width than in

Table 3. Parameters of morphokarst unit and means of dolines variables in the nine samples of the NW sector.

sample	KARE	KMAX	KAVE	KMIN	ATDOL	VTDOL	APER	VCAR	DNUM	DDEN		
t 2	1.41	203	186	150	197617	309751	14.0	219439	63	44.6		
t 3	1.22	237	197	149	301639	655347	24.7	536896	80	65.6		
t 4	1.47	266	225	164	296411	923365	20.1	626605	54	36.6		
t 5	3.68	294	266	212	1263636	3320577	34.3	901939	315	85.5		
t 6	0.85	312	275	228	264334	874973	31.1	1132944	69	81.1		
t 7	3.49	365	334	277	1382550	5185587	39.6	1486845	231	66.2		
Mh	5.60	195	159	117	465198	620533	8.3	110809	55	9.7		
c 1	0.32	315	280	242	136325	430036	42.2	1331381	23	71.2		
c 2	0.29	152	137	119	85298	212476	29.2	729657	25	85.8		
sample	DMAX	DMNR	DAVE	DIDE	E	HMAX	HDOL	HAVE	HVOL	ADOL	VOLU	ID
t 2	68.33	55.76	62.07	62.02	1.22	5.03	2.98	4.01	1.50	3137	4917	52.33
t 3	75.84	58.78	67.30	66.56	1.28	7.79	3.29	5.54	1.99	3770	8192	38.26
t 4	95.95	70.56	83.21	81.18	1.37	9.75	5.04	7.39	2.72	5489	17099	33.97
t 5	78.34	60.77	69.53	68.64	1.28	8.19	4.77	6.48	2.35	4012	10575	32.62
t 6	77.83	60.29	68.98	68.15	1.28	10.04	4.68	7.36	2.83	3831	12681	26.37
t 7	97.96	71.61	83.76	81.09	1.32	10.27	5.18	7.73	3.05	5985	22844	28.63
Mh	116.17	89.26	100.52	99.47	1.31	4.36	1.99	3.12	1.23	8458	11282	98.41
c 1	96.08	69.95	83.02	80.29	1.32	10.30	3.93	7.12	2.51	5927	18690	33.32
c 2	69.43	51.74	60.59	60.21	1.33	8.52	5.50	7.01	2.50	3304	8499	25.72

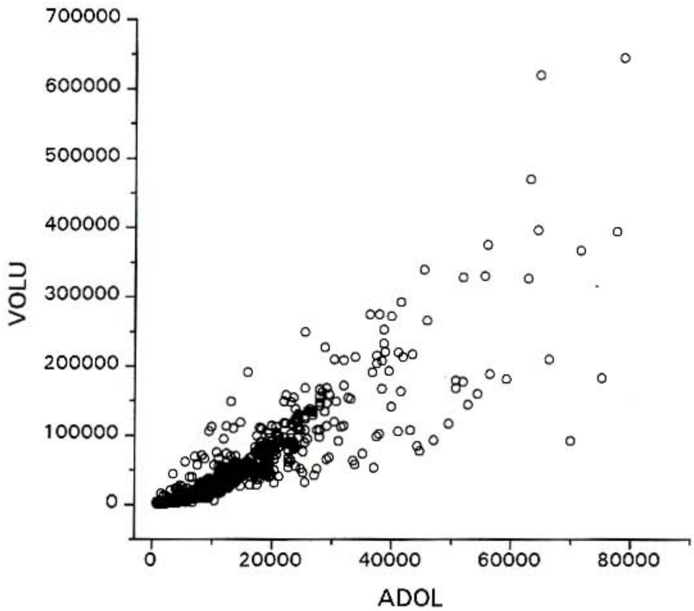


Fig. 12. Distribution of area and volume in the SE group. 9 points are skipped. Linear regression is: VOLU = −30183.4 + 5.8118 × ADOL. R = 0.919.

depth. This hypothesis seems to be strengthened by a high value of ID, pointing out a preferential course of the development in extension.

The hill in Montebelluna (Mh), comparable for its altitude to the 2nd terrace (t2), shows peculiar morphometrical parameters. Whereas the percentage of the surface characterised by dolines (11,5 %) is very close to that of the 2nd terrace (14%), the density is four times lower, since the dolines in this area have a large planimetrical extension which is even wider than the one of the dolines on the 7th terrace. On the contrary the extension in depth is very scarce.

The zone to the north of the highest point of the hill (c1) can be considered the morphological continuation of the western terraces. All morphometrical values are definitely similar to those of the 4th terrace (t4). But there we can find out higher density (DDEN) which determine - equal in planimetrical extension of the depressions – a higher percentage of the surface covered by dolines (APER) than that of all terraces. The volume of the karst relief (VCAR) is second only to that of the highest terrace (t7).

The zone located on the north-east (c2) appears quite different. The dolines present planimetrical values very close to those of the 2nd and 3rd terraces (t2, t3), but the altimetrical development is greater: in this zone the dolines are the most evolved in depth of the whole group, as it is marked by the low value of ID. We must underline that here there is also the highest density in the whole hill.

The SE group

The analysis of the five morphometrical parameters of the dolines, concerning the whole population of this group, marks the morphological and peculiar features of the depressions.

Table 4. Parameters of morphokarst unit and means of dolines variables in the eight samples of the SE sector.

sample	KARE	KMAX	KAVE	KMIN	ATDOL	VTDOL	APER	VCAR	DNUM	DDEN		
s 1	0.48	350	313	280	248044	892049	52.2	1877207	22	46.3		
s 2	0.90	347	320	290	565994	4326657	62.8	4807397	26	28.8		
s 3	0.35	195	171	150	220846	910070	63.7	2627223	23	66.3		
s 4	0.47	290	246	215	268958	1562861	57.1	3319586	24	50.9		
s 5	0.77	237	189	158	355823	2170413	46.3	2829005	22	28.6		
s 6	0.49	183	163	147	301603	1304790	61.5	2662837	32	65.3		
s 7	1.77	185	146	79	574281	3773270	32.5	2137104	32	18.1		
s 8	1.82	203	165	127	1140711	8981410	62.5	4925099	15	8.2		
sample	DMAX	DMNR	DAVE	DIDE	E	HMAX	HDOL	HAVE	HVOL	ADOL	VOLU	ID
s 1	149.00	100.86	124.94	118.30	1.53	15.20	4.66	9.93	3.44	11275	40548	36.69
s 2	174.55	117.50	146.00	137.75	1.40	16.07	7.11	11.59	4.09	21769	166410	33.54
s 3	129.35	90.21	109.80	108.13	1.46	15.34	6.26	10.80	3.80	9602	39568	29.67
s 4	136.40	99.60	118.01	115.10	1.42	19.85	9.79	14.82	5.11	11207	65119	22.98
s 5	178.60	116.60	147.60	140.19	1.48	17.82	6.41	12.11	4.23	19086	108180	34.19
s 6	129.71	84.24	106.98	98.63	1.51	9.39	4.92	7.15	2.56	11831	48883	38.06
s 7	171.03	123.75	147.39	133.11	1.40	16.02	6.13	11.07	3.86	17946	117915	35.6
s 8	455.06	262.65	358.90	302.11	1.64	31.01	10.65	20.83	6.66	102896	800133	45.56

The only morphometrical variables which are definitely linked are ADOL and VOLU, which means that they are common to the whole population of the hill (Fig. 12). The average values of the whole zone come out to be three times higher for the area and about four times for the volume in comparison with the NW group.

An interesting remark can be made with regard to the course of the planimetrical development (ID): the average value (55,6) points out that the depressions have evolved more horizontally than vertically. It is meaningful the comparison with the same variable of the NW group whose average value is 38,99 (see Table 2).

It is possible to distinguish classes of magnitude that group some dolines referable to some evolutive types, but it is remarkable that those types are hardly comparable with other morphological variables such as altitude and the general geographical location.

In order to make a distinction between these types some samples which show quite similar morphometrical values have been chosen (Table 4). Their comparison corroborates what has been already put in evidence by the general analysis: the volume of the karst relief (VCAR) increases from the north to the south together with the size of the dolines. That has been proved analysing three equidistant series of samples lined up from the north to the south. In the first series of samples (s1 – s2), collocated in a subsummit area just on the western edge of the group, a significant increase in the morphometrical averages is marked: ADOL doubles and VOLU quadruplicates.

The increase in depth is not so high: it goes from 9,9 m to 11,5 m (HAVE) and from 3,4 m to 4,1 m (HVOL); in the southern sample it is clear the influence of quite extended but not so deep dolines. At present the density (DDEN) goes from 47,3 to 28,8, whereas the percentage (APER) increases of 10%.

The second series of samples (s3 – s4 – s5), still collocated from north to south, shows a linear trend increasing on the values of volume (VOLU), of area (ADOL) and of diameters (DMAX, DMNR, DAVE and DIDE), whereas the values of depths (HMAX, HDOL, HAVE and HVOL) are at their highest in the middle sample settled just along of the anticline axis. The values of doline density (DDEN) have a decreasing course, like those of percentage (APER): the number of depressions decrease per unit of surface while both their average extension and distance among them increases.

A definitely increasing trend for all variables is verifiable in the third series of samples (s6 – s7 – s8), still located from north to south, on the eastern edge of the hill. The course is quite linear in all variables and it is also marked by a bigger magnitude than the former sample series.

Only the depth values (VDOL and HAVE) do not reflect the same increase. Thus the planimetric dimensions of the dolines in this group tend to grow more than the vertical dimensions as it is also pointed out by the trend of the index of morphological development.

7 *Conclusive remarks*

Montello is the result of the interference between tectonic and mass wasting processes. In particular this very recent morphostructure is the product of the uplifting of a tectonic wedge sculptured by fluvial and karst erosion.

The karst evolution of this morphostructure may seem singular if one considers lithology. This kind of evolution is probably linked with the following predisposing factors:

- the stretching out conditions of the upper part of the tectonic wedge, linked with the strong compression in the deeper part;
- the nearly flat and subhorizontal surfaces of the fluvial rock cut terraces;
- the presence of a thick mantle of regolite cover, deriving mostly from the weathering of the cement of the conglomerate, able to hold water and to release it slowly towards the underlying fissures.

The peculiar epikarst in this regolite cover and in the upper part of the conglomerate is without doubt linked with the style of doline evolution on this karst morphounit.

Even if it is not easy to utilize all the observations derived from the morphological analysis to build a definite evolutionary model of this morphostructure, it is possible to draw some preliminary remarks about two main groups of phenomena:

- typologies and evolutionary aspects of dolines;
- general evolution of the morphostructure.

With reference to the typologies and evolutionary aspects of dolines the following aspects are worth of note. We know that the development and the shape of a doline are directly influenced by the structural, morphological and climatic framework. With regards to morphological setting, we can define "plateau dolines" a large parts of dolines of eastern and western districts, since they developed on sublevel surfaces: in these conditions development and shape are mostly controlled by structural factors.

In the area of the western terraces we distinguish between two morphological typologies of dolines: "terrace-scarp dolines" and "terrace-slope dolines". The former – situated near the base of scarps of the terraces – have a greater development than the other dolines on the same terrace; their hydrographic basin embraces also a sector of the scarp so that they receive a larger quantity of water ("scarp effect"); their shape often comprises a hollow inside the scarp.

The "terrace-slope dolines" are similar to the plateau dolines. They are settled on the northern and southern sides of the terraces, although there are fewer on the latter. Here

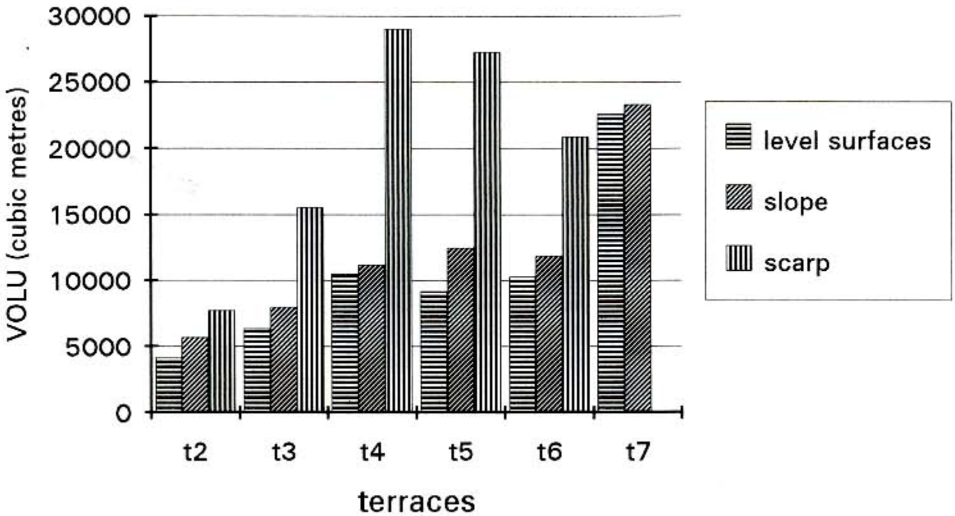


Fig. 13. Means of dolines volume in the western Montello's six terraces. Dolines were distinguished in three group, on the basis of their local placement.

the sublevel surface of the terraces is inclined albeit slightly – outward, since the anticline bending continued after the terrace development. So these dolines tend to evolve as "slope dolines" and get a lengthened shape according to the slope (Fig. 13). That is due to the fact that their hydrographic basin is mostly situated upstream of the absorbing point so that the corrosive action and the development of the basin happens mostly in this area.

In the morphodinamical context of the Montello hill the dolines began to develop as large and shallow forms and their vertical development (depth) is controlled by the time, by the character of the basin (the terrace-scarp dolines are in general deeper than the plateau and terrace-slope dolines), and by the geological structure (the dolines along the anticline axis are deeper than those to the north and to the south of it).

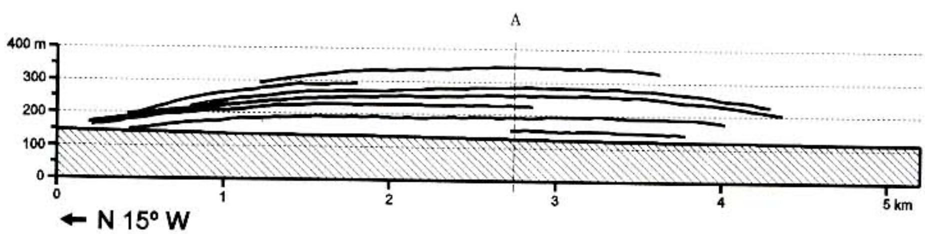


Fig. 14. Sections across the seven western terraces, shown along the anticline axis (A). Altimetric scale is twice the planimetric one.

Résumé. Dans le contexte des Alpes du Sud, le massif du Montello, sorte de bas plateau comparable à un dos de tortue, représente l'un des groupes subalpins les plus singuliers.

Cette morphostructure, constituée par des conglomérats d'âge messinien composés principalement de galets calcaires cimentés par une matrice calcaire, est le résultat d'un bombement causé par la compression d'un compartiment tectonique.

L'émergence graduelle de cette morphostructure au-dessus de la plaine l'a exposée aux différents processus d'érosion: le rôle des rivières a été prédominant au début, tandis que la dénudation karstique est intervenue par la suite.

Les principales sous-unités morphologiques ont été individualisées et analysées au moyen des techniques d'analyse assistée par ordinateur. Certaines d'entre elles présentent des caractères de vastes terrasses rocheuses d'erosion fluviatile. Les caractèristiques des dolines, qui représentent une nombreuse population de plus de 2000 formes, permettent d'évaluer l'âge relatif des surfaces des sous-unités correspondantes.

Les sous-unités de ce massif se divisent en deux groupes: le groupe nord-occidental et le groupe sud-oriental. Les dolines sont plus nombreuses et plus petites au NW qu'au SE.

Dans le groupe nord-occidental, un escalier constitué de sept terrasses rocheuses est aisément identifiable grâce à la bonne corrélation entre le développement volumétrique des dolines et l'altitude des terrasses où elles se localisent.

Les types de dolines suivants ont été distingués dans cette morphostructure: a) les dolines de plateau; b) les dolines situées sur les escarpements de terrasses; c) les dolines situées sur les surfaces des terrasses. Les dolines de plateau sont représentées par celles du plateau sommital du massif; les formes et dimensions des dolines d'escarpement de terrrasses sont influencées par la position de ces dernières au bas des pentes; les dolines des surfaces de terrasses ressemblent aux dolines de plateau, mais sont situées sur des pentes légèrement inclinées par la tectonique (bombement anticlinal de la morphostructure.

Dans le contexte morphodynamique du massif du Montello, les dolines ont commencé à se développer sous la forme de larges dépressions peu profondes et leur développement vertical (profondeur) est fonction du temps, des caractèristiques de leur bassin de réception (les dolines se développant à coté des escarpements des terrasses sont en général plus profondes que celles situées sur plateau et sur les surfaces des terrasses) et de la structure géologique (les dolines qui se trouvent le long de l'axe anticlinal sont plus profondes que celles qui se situent au nord et au sud de ce dernier).

En référence à l'évolution générale de cette morphostructure, il est possible de déterminer un âge plus ancien pour les surfaces situées au centre et dans la partie orientale du massif. Ce fait pourrait être lié à une "émersion" plus ancienne de cette partie de la morphostructure et peut-être à une migration graduelle vers l'ouest du bombement du massif.

Zusammenfassung. Das Montellomassiv, ein tiefes Plateau in Form eines Schildkrötenrückens, ist eine einmalige subalpine Gruppe in den Südalpen.

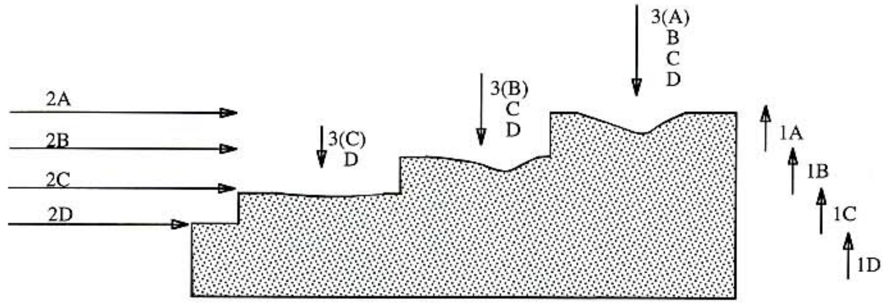
Diese morphologisch gewölbte Struktur entstand durch eine Kompression der tektonischen Einheit und besteht aus Konglomeraten des Messinienalters, einem Kalkgeröll mit Karbonatzement. Durch die sukzessive Emersion wurde diese morphologische Struktur den Erosionsprozessen ausgesetzt: Die Rolle der Flüsse ist vorherrschend und die Karstdenudation sekundär.

Die wichtigsten morphologischen Untereinheiten wurden computergestützt unterschieden und analysiert. Einige davon können als weite, zerschnittene Felsterrassen beschrieben werden. Über 2000 Dolinen erlauben eine Altersabschätzung der entsprechenden Untereinheiten, welche in zwei Gruppen geteilt sind: die Nordwest- und die Südostgruppe. Die NW-Dolinen sind kleiner und zahlreicher als diejenigen im SE. In der NW-Gruppe kann eine Treppe von sieben Felsterrassen dank der guten Korrelation zwischen der Dolinenvolumina und den Terrassenhöhen leicht identifiziert werden.

In der morphologischen Struktur kann man drei Dolinenarten unterscheiden:

a) Plateaudolinen, die sich zuoberst auf dem Plateau befinden.

b) Felsvorsprungfussdolinen, die durch den Felsvorsprung der Terrassen beeinflußt werden.



1 = tectonic episodes of uplifting
2 = fluvial phases of lateral erosion
3 = surface karst morphogenesis
A, B, C, D = episodes and/or phases
(A is the oldest; D the most recent)

Fig. 15. The sketch outlines the sequence of cycles each composed by: a) a tectonic uplifting episode, b) a fluvial erosion phase, c) a surface karst morphogenetic phase.

With reference to the general evolution of the morphostructure it is possible to recognise the older age of the central and eastern surfaces. This could be related with a former "emersion" from the alluvial covers of the plain of these parts of the morphostructure and perhaps with a westward migration of the up-bulging of the hill.

Most of the sub-units of the morphostructure probably started as "erosional fluvial terraces" after modified both by tectonic uplifting and bending and by the erosional processes (Fig. 14).

Surely the remarks presented above delineate only some preliminary results of this research. In fact in the future we will search to make use of the collected data:

1) to modelize the time evolution of dolines;
2) to modelize the first evolutionary phases of this alpine neo-morphostructure;
3) to conceive the time and space inter-relations between different morphogenetical processes and phases.

We have to look for a solution for the following problems:

- how to link the size scale of the steps with the time scale;
- how to link the magnitude scale of the dolines on the different steps with the time scale.

The development of the steplike profile of the western side of the ridge seems to be mostly linked with an uplifting by fits and starts, rather than with the alternance of diverse morphoclimatic phases during late Pliocene and Pleistocene. The sketch outlines the sequence of cycles each composed by: a) a tectonic uplifting episode, b) a fluvial erosion phase, c) a surface karst morphogenetic phase (Fig. 15). In any case, fluvial erosion of terraces operates on a band inside a limited space and time span, while surface karst morphogenesis is continuing to work on all the hilly surfaces, except the steeper scarps.

References

ABRAMI, G. & F. MASSARI (1968): La morfologia carsica del colle del Montello. – Riv. Geogr. It. **75**: 1-45.

BOCCALON, G., F. CUCCHI & P. FORTI (1987): The hydrology of the Montello karst area. – Geolis **1**: 62-78.

BONDESAN, A., M. MENEGHEL & U. SAURO (1993): Morphometric analysis of dolines. – Internat. Journal of Speleology. **21**: 55 pp.

CASTIGLIONI, G.B., M. MENEGHEL & U. SAURO (1989): Elementi per una ricostruzione dell'evoluzione morfotettonica delle Prealpi Venete. – Geogr. Fis. Dinam. Quat., suppl. **1**: 31-43.

COMEL, A. (1955): I terreni dell'alta pianura trevigiana compresi nel foglio "Conegliano". – Ann. Staz. Chim.-Agr. Sperim. di Udine, ser. **3/8**: 1-30.

CUCCHI, F. (1978): Indagini strutturali su alcune cavità del Montello Nord-orientale (TV). – Mondo sotterraneo **2/1**: 13 pp.

DAL PIAZ, G. (1942): L'età del Montello. – Commentationes **6**: 475-494.

DALL'ARCHE, L. & A. ZANFERRARI (1979): Sull'origine e l'età di alcuni depositi conglomeratici della valle del Fiume Soligo (Prealpi Venete orientali). – Studi Trentini di Scienze Naturali **56**: 53-67.

FORD, D. & P. WILLIAMS (1989): Karst geomorphology and hydrology. – 601 pp., Chapman & Hall, London.

MASSARI, F. (1975): Sedimentazione ciclica e stratigrafica del Tortoniano superiore-Messiniano tra Bassano e Vittorio Veneto. – Mem. Ist. Geol. e Miner. Univ. Padova, **31**: 58 pp.

MENEGHEL, M., U. SAURO, M. BACIGA, A. FILECCIA, G. FRIGO, V. TONIELLO, D. ZAMPIERI (1986): Sorgenti carsiche ed erosione chimica nelle Prealpi Venete. – Studi Trentini di Scienze Naturali, Acta Geologica **62**: 145-172.

MIETTO, P. & U. SAURO (1989): Paesaggi carsici e grotte del Veneto. – 415 pp., Regione del Veneto & La Grafica, Vago di Lavagno – Verona.

MIETTO, P. (a cura di) (1993): Elenchi catastali delle grotte e delle aree carsiche del Veneto. – Speleologia Veneta, suppl. **1**: 101 pp.

Regione del Veneto (1987): Catasto regionale delle grotte. – BUR, suppl. al n° **28** del 20/05/87.

– (1990): Carta Geologica del Veneto alla scala 1:250.000 con note illustrative. – 31 pp., Regione del Veneto, Carta con note illustrative.

SACCARDO, A. (1885): Ricerche intorno alle erosioni del Montello. – Atti Soc. Veneto-Trentina Scienze Naturali, **9/2**: 16 pp.

SAURO, U. (1987): Aspetti morfologici del Montello. – In: Amministr. e Bibliot. Comunali dei Comuni di Crocetta, Giavera, Nervesa e Volpago, "Atti del convegno di studi naturalistici sul Montello". Nervesa della Battaglia, 7 giugno 1987.

STELLA, A. (1902): Il Montello: descrizione geognostica agraria. – Tipografia nazionale di G. Bertero, Roma.

TONIOLO, A. R. (1907): Il colle del Montello. – Mem. Geogr. della Reale Soc. Geografica Italiana **1**: 257-373.

– (1914): L'idrografia del Quartier del Piave. – Giornale di geologia pratica, **12/4**: 3-57.

VENZO, S., F. CARRARO & F. PETRUCCI (1977): I depositi quaternari del Neogene superiore nella bassa valle del Piave da Quero al Montello e del Paleo-Piave nella valle del Soligo. – Mem. Ist. Geol. e Miner. Univ. Padova, **30**: 64 pp.

Topographical maps utilised

– Carta Tecnica Regionale, alla scala 1:5.000:

Elemento n° 084102 "Sernaglia della Battaglia Sud"
084113 "Falzé di Piave"
084131 "Grave di Ciano"

084132 "Crosera"
084133 "Nogarè"
084141 "Santi Angeli"
084142 "Sacello
084143 "Santa Maria della Vittoria"
084144 "Capitello dei Lupi"
084154 "Ossario del Montello"
084153 "Sovilla"
105011 "Montebelluna"
105014 "Caerano San Marco"
105021 "Selva del Montello"
105024 "Volpago del Montello

– Carta Tecnica Regionale, alla scala 1:10.000:
Sezione n° 084130 "Cornuda"
084140 "Santa Maria della Vittoria"
084150 "Nervesa della Battaglia"
105010 "Montebelluna"
105020 "Volpago del Montello"

Address of the authors: FRANCESCO FERRARESE, UGO SAURO and CHRISTIAN TONELLO, Dipartimento di Geografia, Via del Santo 26, I-35123 Padova, Italy.

c) Hangterrassendolinen, die den Plateaudolinen ähnlich sind und sich auf dem Terrassenhang der Antiklinalwölbung befinden.

Die morphologische Dynamik des Montellomassivs begann mit breiten und seichten Dolinen. Die Entwicklung der Dolinentiefe ist Funktion der Zeit, der Art (Felsvorsprungfußdolinen sind meist tiefer) und der geologischen Struktur (Dolinen auf der Antiklinalachse sind tiefer).

Man kann mit der morphologischen Evolution ein höheres Alter für das Zentrum und den Ostteil ausmachen. Der Grund könnte in einer früheren „Emersion" und der wandernden Wölbung des Massivs Richtung Westen liegen.

1 *Introduction*

The landforms of the high mountain karst are the result of a long geo-dynamical history. The relief is the expression of the superimposition of several morphogenetical phases, which have marked the dismantling of thousands of metres of the cover rocks. For a geomorphologist who analyses the present landscape it is difficult to recognise and distinguish the heritage of such a complex a history.

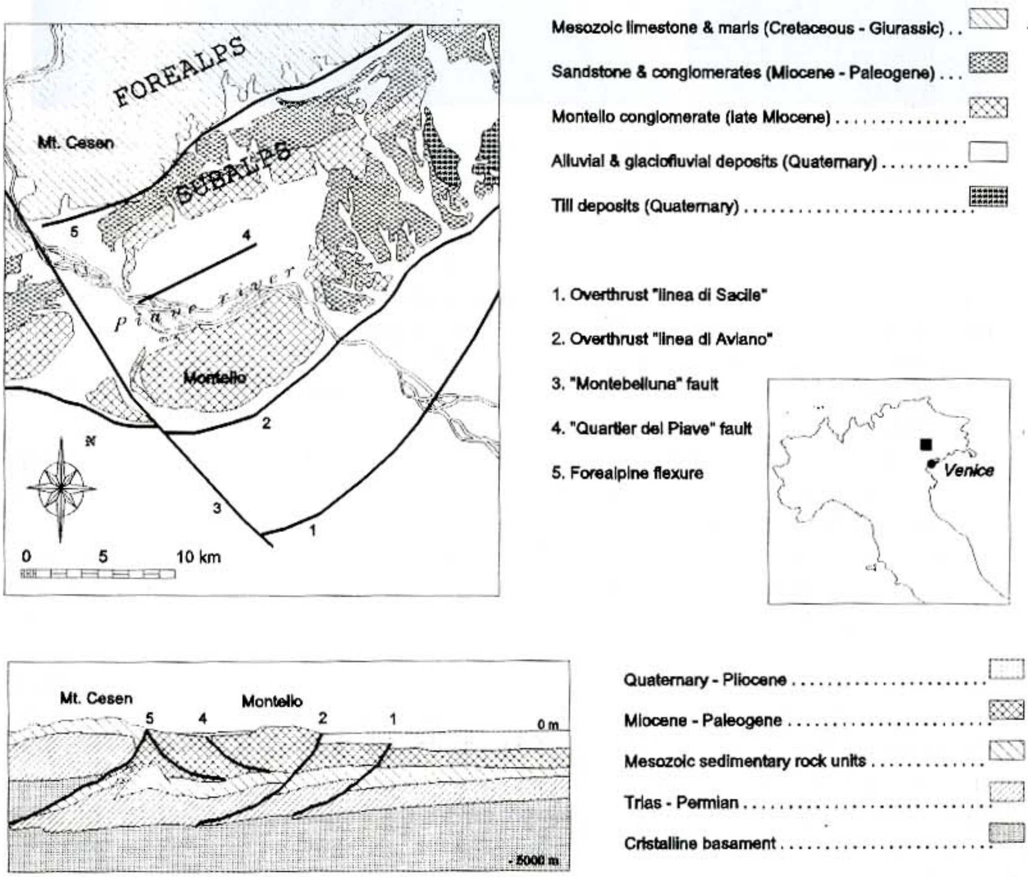


Fig. 1. Geological sketch of the Montello area.

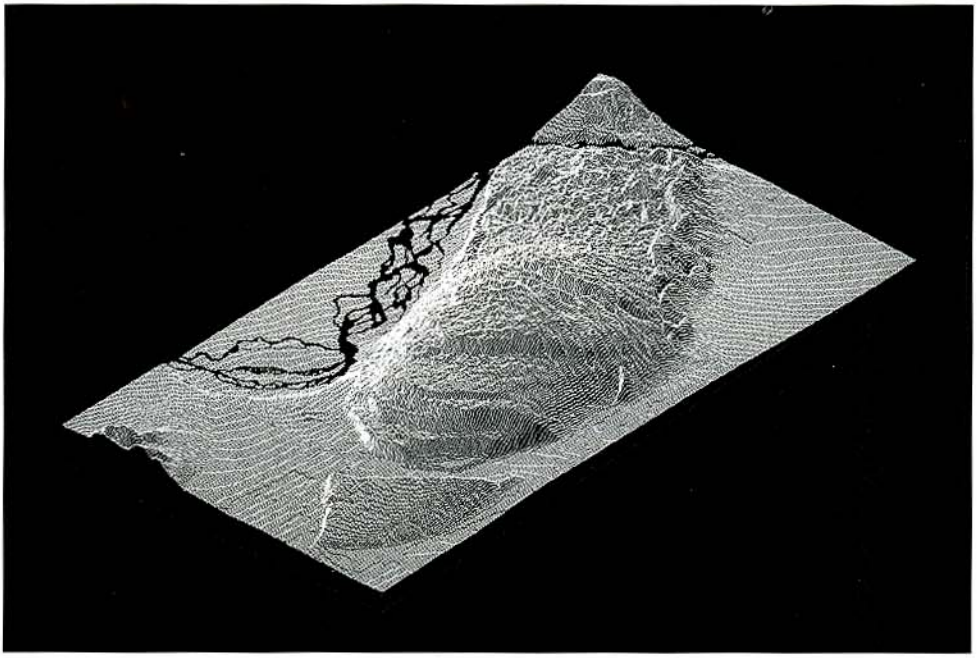


Fig. 2. Digital elevation model of Montello & Montebelluna hill shown from S-SW. The vertical scale is exaggerated.

In any case, in the alpine relief it is also possible to see very young morphostructures, which have just begun their rising, and are now in their embryonic stage. Most of these young morphostructures are shaped by fluvial morphogenesis. The karst evolution of one of these units is an unusual event.

In the Southern Alps the outer mountain belt is constituted by the Fore-Alps, a complex ridge dissected by large valleys into well defined mountain groups.

Seen from the Venetian Plain, these groups show a very steep and high tectonic scarp, a kind of wall. Underneath this scarp there are some hilly ridges, often isolated in the high plain, which have been called "Colline Sub-alpine" (sub-alpine hills).

Between these hills, Montello ridge is the most singular, a kind of low plateau comparable to a turtleback. This relief, extended in a WSW-ENE direction, is about 13 km long, 5 km wide and shows an average elevation of about 100 m (maximum of 280 m) above the plain.

This morphostructure is the expression of the up-arching by compressional shortening of a tectonic wedge delimited on the SSE side by an overthrust (Aviano line) and on the NNW side by a backthrust (backthrust of Montello) (Fig. 1).

The geological formation, which constitutes this relief, is a nearly 2000 m thick conglomerate (Montello Conglomerate), formed mostly by limestone pebbles bound by a carbonatic cement. It is part of a messinian age delta fan, showing in its upper part also alluvial deposits. The accumulation of this delta fan may be correlated with the main uplifting phase of the south alpine chain during the Neogene.

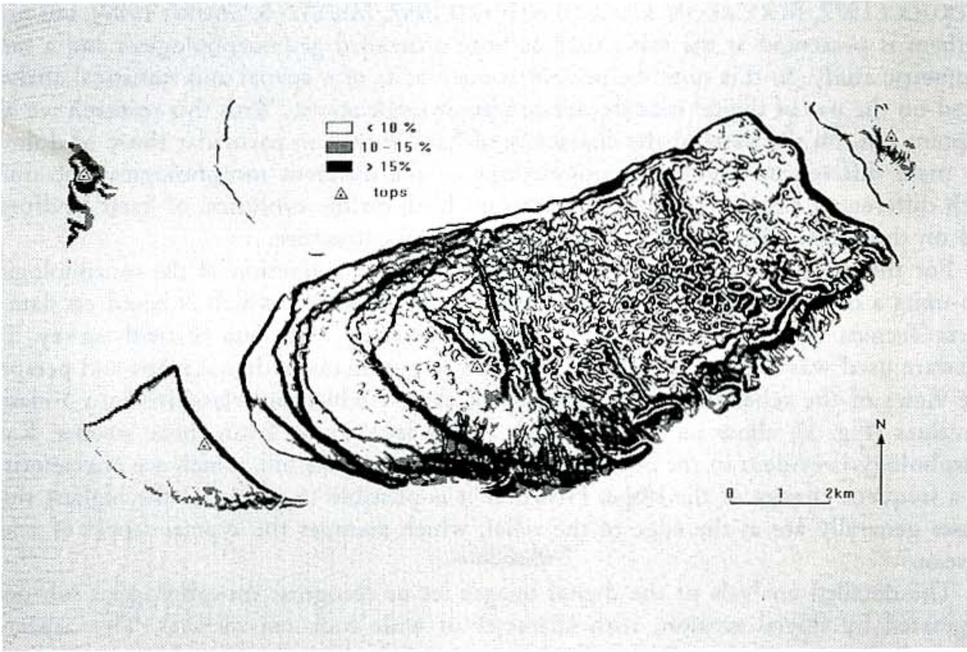


Fig. 3. Map of slope (three classes distinguished in percent values) in Montello and Montebelluna hill.

So this morphostructure has begun to bulge very recently, from no longer than 5 million years. During its history, the erosion has removed no more than a few hundred metres of rocks.

The gradual upsurge of the morphostructure above the plain has exposed it to the erosional processes first of all by the rivers and secondarily by karst denudation. The fluvial erosion, which is still active nowadays on the northern side of the ridge, has utilised the transported pebbles as tools to perform bottom and lateral erosion in the hard rock of the river bed.

The uplifting prevailed upon erosion and a hill was formed, the surface of which is a step of erosional surfaces of increasing ages, from the lowest to the top one.

The degree of development of karst basins, of doline type (sink-holes), depends on the age of the surfaces. In the following pages we both describe, on the base of a computer aided analysis, the main morphological sub-units and analyse, from the morphometrical point of view, the degree of development of the dolines. The results of analysis are discussed inside the framework of the geodynamical evolution of these morphounits.

2 *Geomorphological Aspects of Montello Ridge*

Montello ridge has been the object of numerous publications (SACCARDO 1885, STELLA 1902, TONIOLO 1907, DAL PIAZ 1942, ABRAMI & MASSARI 1968, VENZO, CARRARO &

PETRUCCI 1977, BOCCALON, CUCCHI & FORTI 1987, MIETTO & SAURO 1989), but none of them is presented at the same time as both a detailed geomorphological and a morphometric study. In this note we present some results of a spatial and statistical analysis based on the use of digital models and computer applications. With this research we aim to point out, on the basis of the characters of karst forms, in particular those of dolines, the main differences among the populations of the different morphological sub-units. Such differences supply interesting indications both on the evolution of karst landforms and on the geodynamic history of the whole morphostructure.

For the morphological analysis of the area and the distinction of the morphological sub-units a digital elevation model has been created (Fig. 2) , which is based on data of Carta Tecnica Regionale of Veneto (1:10000) integrated with data of field survey. The software used was G.I.S. IDRISI which allows to get thematic digital maps and perspective views of the relief (D.E.M.). The map of slope , which are classified into 3 classes of values (Fig. 3), allow us to distinguish nearly level zones from those steeper. Karst morphology is evident in the central and east sections of the hill, which are characterised by a frequent change of the slope. However it is possible to note that the highest slope values generally are at the edge of the relief, which assumes the typical aspect of a low plateau.

The detailed analysis of the digital images let us recognise morphological sub-units originated by fluvial erosion, with character of wide rock cut terraces. This aspect is evident in the west section of the hill where, west of the highest point, there is a sequence of seven terraces which mark the transition from the alluvial plain to the top of the hill (SAURO 1987).

Montebelluna hill rises with a steep slope, which is less than a kilometre west of the western edge of Montello (Capo di Monte, 195 m a. s. l.). This hill represents the continuation of Montello morphostructure. The depression which separates these two units corresponds to a segment of dead valley which may be interpreted as an entrenched meander of a paleo-river.

Another evident terrace is the north strip of the Montello plateau, a narrow sublevel surface which is about 150 m wide. To its south there is a system of scarps which are less evident and cross the hill parallel to its axis.

East of the top point it is possible to recognise systems of linear valleys which cross the hill with N-S and NW-SE direction. More eastwards a plateau extends which is characterised by a honeycombs morphology.

The southern side of the relief is ploughed by frequent fluvial-karst valleys which are intercepted in the central-east section by a series of deeper valleys sub-parallel to the orographic axis of the hill.

To the different morphological sub-units correspond particular expressions of the karst relief, which is diversified according to the slope, to the presence of systems of fractures and to the age of the surface.

3 *Dolines research methodology*

The individuation and localisation of dolines in the ambit of various sub-units took place using the Carta Tecnica Regionale del Veneto (scale 1:5.000). Later the stereoscopic vision of aerial photos permitted to determine with precision the perimeter of the depressions and to locate other dolines which were not drawn on the map. Those dolines have been the object of field survey. The software G.I.S. IDRISI represented an important instrument for the morphometric analysis of dolines.

4 *Morphometric parameters and their calculation*

The below listed parameters for the morphometric analysis of dolines have been chosen on the basis of a recent study (SAURO, MENEGHEL & BONDESAN 1992). Moreover, a few other variables derived from algebraical calculations have been considered[1].

Doline parameters

1) Linear planimetric parameters:
- Maximum diameter (DMAX): the length in metres (m) of the segment linking the two most distant points of the perimeter.
- Minor diameter (DMNR): the longest segment in metres linking two points of the perimeter and perpendicular to the maximum diameter.
- Average diameter (DAVE): the arithmetical average in metres of DMAX and DMNR.
- Ideal diameter (DIDE): the diameter in metres of the circle having the same area of the doline. It is an index of planimetric extension, such as ADOL and DAVE, because it leads all the dolines to the same shape - the circular one.

2) Areal planimetric parameters:
- Area (ADOL): the planimetric surface bordered by the perimeter, measured in square metres.

3) Altimetric parameters:
- Maximum depth (HMAX): difference in height in metres between the maximum altitude of the perimeter and the lowest point of the depression.

---

[1] Linear variables have been calculated directly on the map or, for those dolines which were the object of field survey, on the planimetry which has been drawn from the measurements on the field. Lots of depth values have been obtained by field survey. The calculation of area has been done by G.I.S., previous digitizing of the perimeters of the dolines; to the same informative system has been trusted the calculations of the coordinates of bottom points and of the volumes of some dolines which have been surveyed on the ground and for which a digital elevation model (D.E.M.) has been created. The volume of the dolines surveyed on the field has been calculated using the Simpson formula modified:

$$V = A_1/(h/3) + ((A_2+A_3)/2)xh + ... + ((A_{n-1}+A_n)/2)xh$$

where: V = doline volume, $A_{1...n}$ = areas of the following contourline, h= equidistance of contourline (1 m).

For all the other dolines volume has been calculated using the cone formula modified:

$$V = ADOL \times (HAVE/3+k)$$

where the empiric correction k, between 0,5 and 0,7 results from the comparison between the volume calculated with the cone formula and that one calculated using the Simpson formula, more precise, in the dolines surveyed on the field.

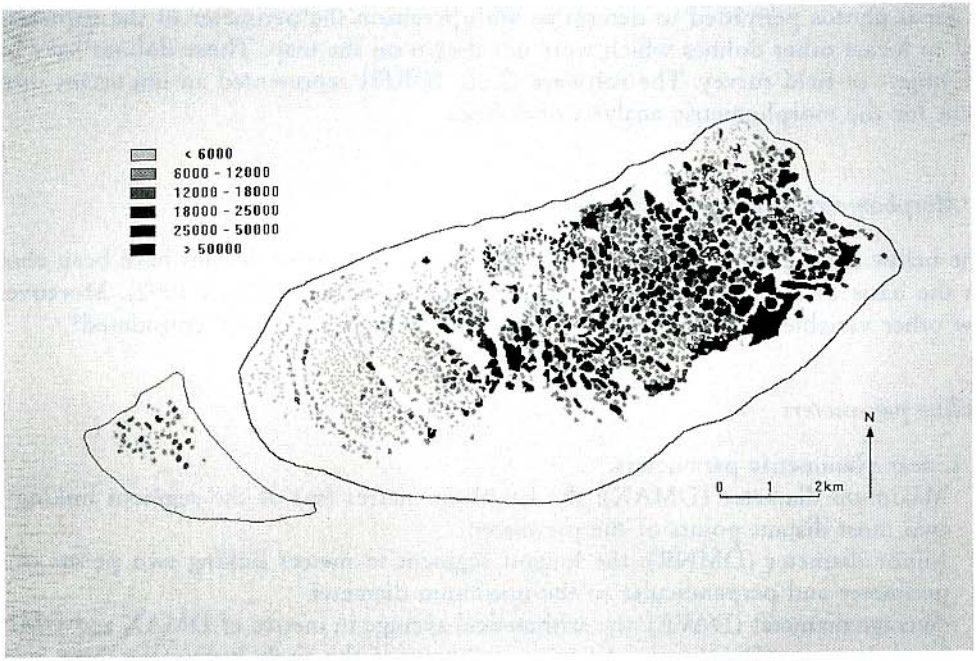


Fig. 4. Map of area's (ADOL) classes of dolines in square metres. It is possible to distinguish clearly Montello's western terraces.

- Minimum depth (HDOL): difference in height in metres between the minimum altitude of the perimeter and the lowest point of the depression.
- Average depth (HAVE): arithmetical average of HMAX and HDOL.

4) Computed parameters:
- Volume (VOLU): volume of doline in cubic metres.
- Eccentricity (E): DMAX/DMNR ratio. Larger than 1 (1 = perfectly circular doline) this value is, more elliptical the border of the doline becomes. Eccentricity index loses in significance in the case of dolines with winding-amoebic border.
- Volumetric depth (HVOL): VOLU/ADOL ratio. The height in metres of a cylinder in which volume and area of the circular section are those of the doline.
- Index of morphological development (ID): DIDE/HVOL ratio. It indicates if the dolines developed preferably depthwards (ID low) or in planimetric extension (ID high).

After having calculated the different morphometric parameters of the various populations of dolines it was possible to go on with the calculation of the quantitative parameters of the morphokarst sub-units.

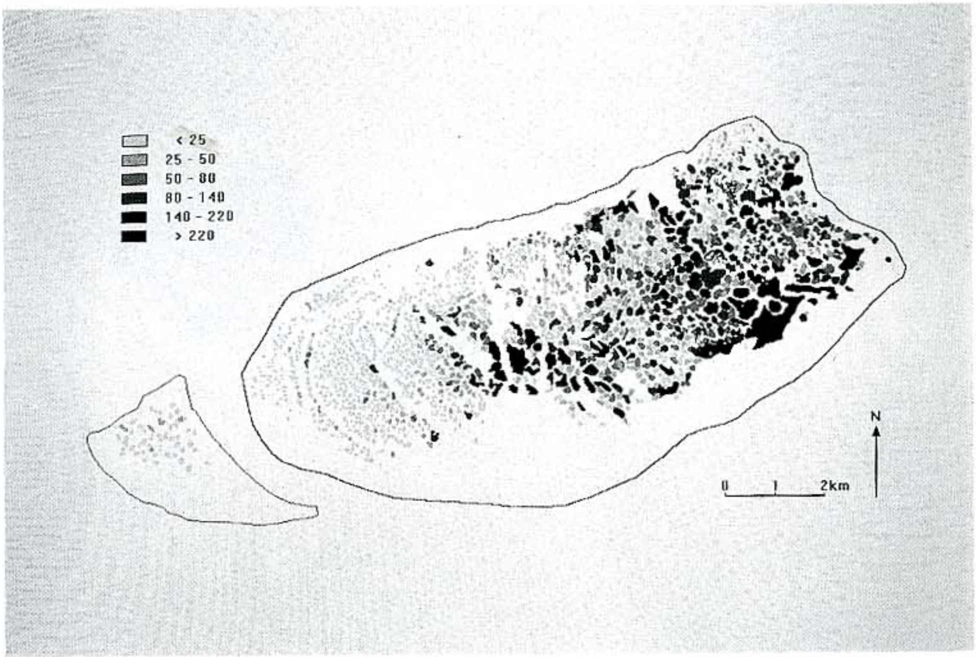


Fig. 5. Map of volume's (VOLU) classes of dolines ($m^3 \times 1000$). Highest values are located in the centre and in the SE parts of Montello.

Quantitative parameters of a morphokarst unit

- KARE: total surface of a karst area in square kilometres.
- DNUM: total number of dolines.
- DDEN: depression density expressed as the number of dolines per square kilometre (DNUM/KARE).
- ATDOL: total surface covered by dolines, expressed in square metres: Σ ADOL.
- APER: percentage of surface covered by dolines.
- VTDOL: total volume of the dolines inside the morphological unit. It is expressed in cubic metres: Σ VOLU.
- VCAR: ratio between VTDOL and KARE (m^3/km^2): it is a good index of the stage of karst evolution expressing the entity of the differential karst erosion between different morphokarstic units or sub-units.
- KMAX: maximum altitude of the karst area (in metres a.s.l.).
- KMIN: minimum altitude of the karst area.
- KAVE: average altitude of the karst area.

5 *Morphometric analysis*

For reasons of space it is impossible to debate all the results of the morphometric analyses. Therefore, the discussion will be limited to some of the most important points. The five