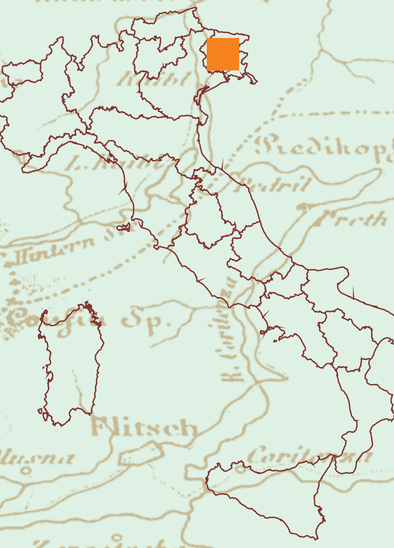

The Late Quaternary evolution of the Friuli upper plain (NE Italy)

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ABSTRACT

The central Friuli upper plain and the Tagliamento Moraine Amphitheatre (NE Italy) provide good evidence of how the joint analysis of field survey data and surface digital representations (DEM derived maps) can enable more careful geological mapping and a more accurate analysis of landforms and the related forming processes. During the Late Pleistocene and the Holocene, climate fluctuations, active tectonics, and erosional and depositional processes repeatedly affected the study area, leading to a complex evolution in the landscape. The step-by-step reconstruction introduced here is based on recent field data supported by microrelief, shaded relief and 3D map analyses (DEMs). In addition, the advantages of surface digital representations in understanding the evolution of the study area are considered and discussed in terms of methodology.

AIMS

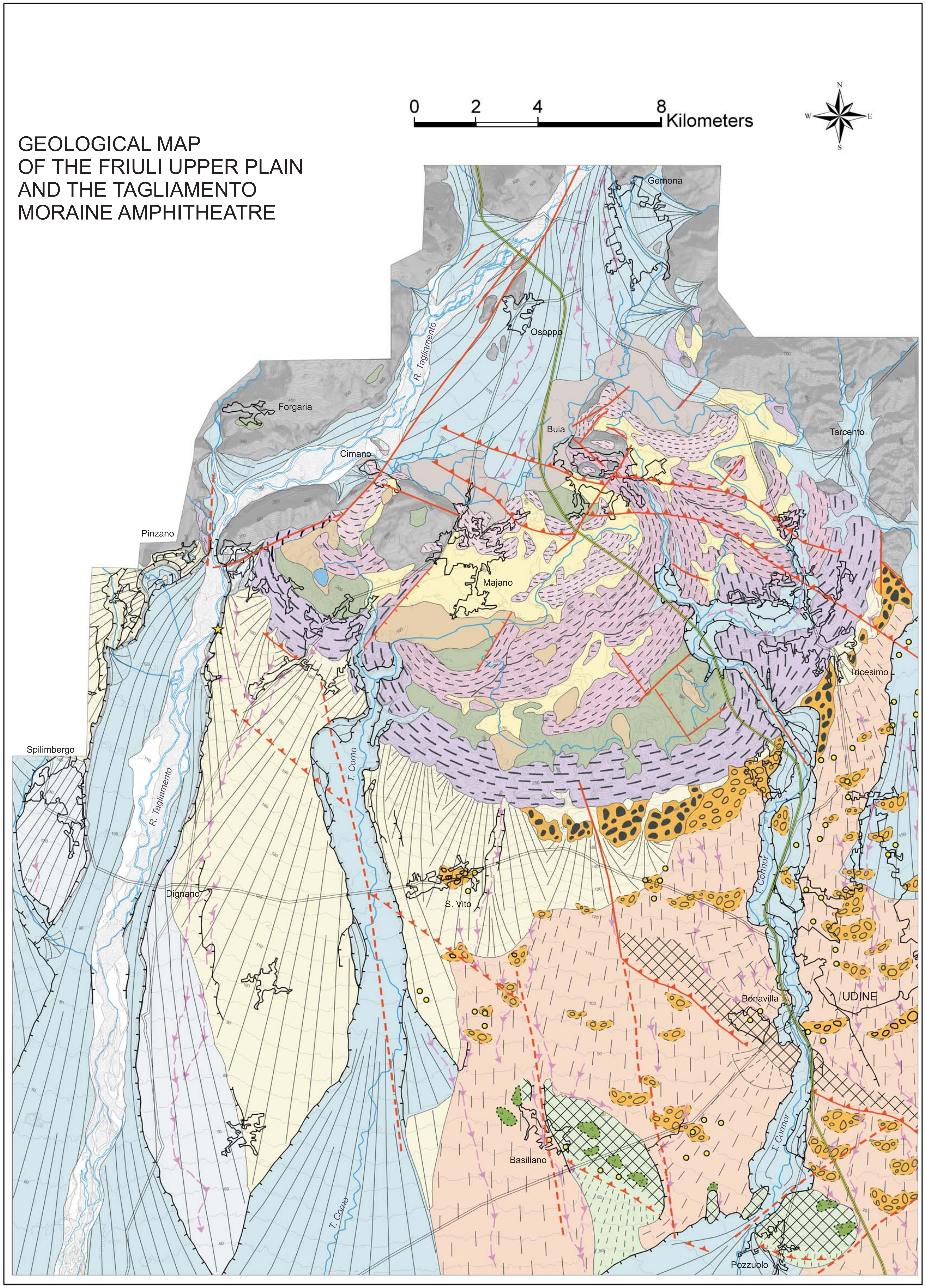
The study aims to show how field survey and DEM-derived map analyses can be successfully combined in interpreting the evolution of an area consisting of alluvial, glacial and glaciofluvial Quaternary deposits, and affected by active tectonics.

KEY WORDS

Carnic and Julian Alps, Friuli upper plain, River Tagliamento, Tagliamento Moraine Amphitheatre, Late Pleistocene, Holocene, Glacialism, Glaciofluvial deposits, Active tectonics, Palaeodrainage.

RIASSUNTO

L'alta pianura friulana e l'Anfiteatro morenico del Tagliamento (Italia NE) permettono di dimostrare come, attraverso l'abbinamento tra il classico rilevamento geologico di terreno e l'utilizzo delle moderne tecniche informatiche di rappresentazione tridimensionale del territorio, si possa ottenere una mappatura geologica del territorio arricchita di precise indicazioni geomorfologiche e dei relativi suggerimenti genetici. Durante il Pleistocene Sup. e l'Olocene il settore di studio fu soggetto a ripetute fluttuazioni climatiche glaciali-interglaciali, ad attività tettonica e ciclici processi erosivo-deposizionali che diedero origine ad una complessa evoluzione del territorio. La ricostruzione delle tappe evolutive dell'area indagata si basa su recenti dati di terreno valutati alla luce dell'analisi compiuta sui DEM (carte del microrilievo, rilievi ombreggiati e ricostruzioni 3D del territorio).
Inoltre, dal punto di vista metodologico, si evidenziano i vantaggi offerti dalle analisi compiute sulla topografia vettoriale per mezzo delle moderne tecniche digitali.



Fluvial corridor active deposit *Upper Holocene*	14	Coarse bimodal gravel with very few sand lenses, organised in longitudinal bars dissected by low water flows. Thickness up to a few metres.
Alluvial upper plain deposit and fan inactive deposit *Lower Holocene*	13	Locally-cemented gravel, with scanty sandy matrix, in metrical graded bodies with erosive base. Coarse sand and less frequent mud in thin lenses. Thickness up to a few tens of m.
Lacustrine deposit back to moraine arc *Upper Pleistocene (late glacial)*	12	Laminated clay and silt with muddy sand and rare gravelly mud in thin mud-flow horizons. Thickness up to 30 m.
Glaciofluvial deposit (11a in Fig. 9) and fluvial fan deposit (11b in Fig. 9) *Upper Pleistocene (LGM)*	11	Coarse and well-sorted gravel and conglomerate in bodies 2-5 m thick. Mud and muddy sand in scattered and thin layers ($\phi < 1$ dm). Thickness up to 30-50 m.
Peat deposit of intermorainic area *Pleistocene-lower Holocene*	10	Dark brown and black peat in thin horizons interbedded with massive mud, clay and scanty fine sand. Thickness up to a few metres.
Glaciofluvial intermoraine deposit *Upper Pleistocene (LGM)*	9	Gravel, sandy gravel and less matrix supported gravel, coarse to fine sand lenticular bodies, locally graded. Thickness a few metres.
Lodgement till (I-II: recessional arcs) *Upper Pleistocene (LGM)*	8 (I / II)	Diamicton made of gravel, sand and mud. Thickness up to several tens of metres.
Coarse lodgement till (terminal arcs) *Upper Pleistocene (LGM)*	8	Diamicton made of gravel, sand and mud. Oversized boulders ($\phi > 1$ m) are common especially in the terminal moraine arc. Thickness up to 150 m.
Fine lodgement till *Upper Pleistocene (LGM)*	7	Diamicton made of prevailing mud with pebbles and sand. Thickness up to a tens of a few metres.
Alluvial upper plain deposit and fluvial fan deposit *Pleistocene (pre-LGM)*	6	Gravel and sandy gravel and conglomerates in 3-5 m thick channelised bodies. Frequent yellowish sand and laminated mud with organic matter, in levels up to 2.5 m. Scattered palaeosoil horizons (2-60 cm). Thickness over 30 m.
Glaciofluvial deposit of outwash plain *Pleistocene (pre-LGM)*	5	Gravel and less sandy gravel in graded beds organised in metrical bodies, well cemented in places. Thin lenses of sand and mud. Thickness up to several tens of metres.
Till (a: outcropping; b: sub-outcropping) *Pleistocene (pre-LGM)*	4 (a / b)	Diamicton made of pebbles, cobbles and scattered but frequent boulders ($\phi > 1$ m) in mud matrix, abundant in places. Locally gravel and sand interbed in dm-m thick lenses. Thickness ranges from a few metres up to 30 m.
Glaciofluvial deposit of outwash plain *Pleistocene (pre-last interglacial)*	3	Well to poorly-cemented and deeply altered conglomerate and gravel. A thick intercalation of red clay with deeply altered pebbles is present in well drillings. The lithosome rests on Tortonian sandstones. Thickness about 50 m.
Till (sub-outcropping) *Pleistocene (pre-last interglacial)*	2	Diamicton made of deeply altered clasts and boulders ($\phi > 0{,}5$ m) in mud matrix. Thickness cannot be established precisely.
Bedrock *Cretaceous-Palaeogene-Miocene*	1	Mainly limestones and dolostones in the northern relifs; conglomerates and sandstones in the southern outcrops.

Symbols

Holocene	Subvertical fault (held active)
Pleistocene	Subvertical fault (inactive)
Holocene	Normal fault (held active)
Holocene	Buried thrust (held active)
Neogene	Buried thrust (inactive)

Tectonics

- Aonedis N section
- Morphotectonic high (from 4 to 12 m)
- Erratic boulder ($\phi > 1$m) in outcrop, cave or well
- Trace of abandoned stream
- Erosion scarp edge
- Tectonically tilted flow spreading directions
- Flow spreading directions

Fig. 1 - *Geological map of the central Friuli area (Pleistocene-Holocene succession). Geological survey has been performed by A. Astori and C. Venturini.*

GEOLOGICAL SETTING

The study area is located on the southern border of the Carnic and Julian Alps (Friuli Region), belonging to the eastern Southern Alpine belt. The Southern Alps are a post-collisional chain inside the Alpine belt s.l. The innermost part of the easternmost Southern Alps is made of Ordovician-Carboniferous rocks, strongly deformed during the Hercynian orogeny (VENTURINI & SPALLETTA, 1998) in Bashkirian times.

The Hercynian core (i.e. the Palaeocarnic Chain) is an E-W elongated strip extended between Austria and Italy for about 120 km by 5 to 15 km of width, bordered to the north by the eastern segment of the Insubric Lineament (Gailtal line), which separates the Austroalpine and Southalpine domains.

Towards south, Upper Palaeozoic and Triassic successions cover the Hercynian units with angular unconformity. In places, the Hercynian belt is unconformably capped by a Permo-Carboniferous sequence (upper Moscovian-upper Artinskian) consisting of alluvial-deltaic to marine shallow water deposits (0-2,000 m) stored up in narrow pull-apart basins which have experienced syn-sedimentary tectonics (VENTURINI, 1991; VENTURINI & SPALLETTA, 1998; VAI & VENTURINI, 2002).

In the Carnic and Julian Alps, the stratigraphic succession affected by Alpine deformations is over 14 km thick, and consists of a well-preserved, sedimentary and partly volcanic succession of Ordovician-Miocene age.

In the Friuli area, most of the Alpine belt consists of Triassic-Jurassic carbonates. The outer belt mainly consists of Upper Cretaceous-Palaeocene limestones and Middle Eocene foredeep turbiditic deposits.

These are unconformably sutured by 2 km of Miocene shallow water to fluvial sediments originated from the erosion of the southward prograding Alpine belt. The outermost part of the eastern Southern Alps and their foreland are buried below the Quaternary glacial, glaciofluvial and fluvial sediments of the Friuli and Venetian upper plains (Fig. 2).

The Alpine tectonic setting of the Carnic Alps formed during Cenozoic times. Several deformation sets, each of them due to variations in the orientation of compressional maximum stress, superimposed in the same rock volume. The earliest compression phase recorded in the area is related to the Mesoalpine (Dinaric *Auctorum*) NE-SW-trending stress (middle-late Eocene).

Its effects are mainly recognizable in Slovenia and in the south-eastern part of the Regione Friuli (DOGLIONI, 1987; VENTURINI & TUNIS, 1988).

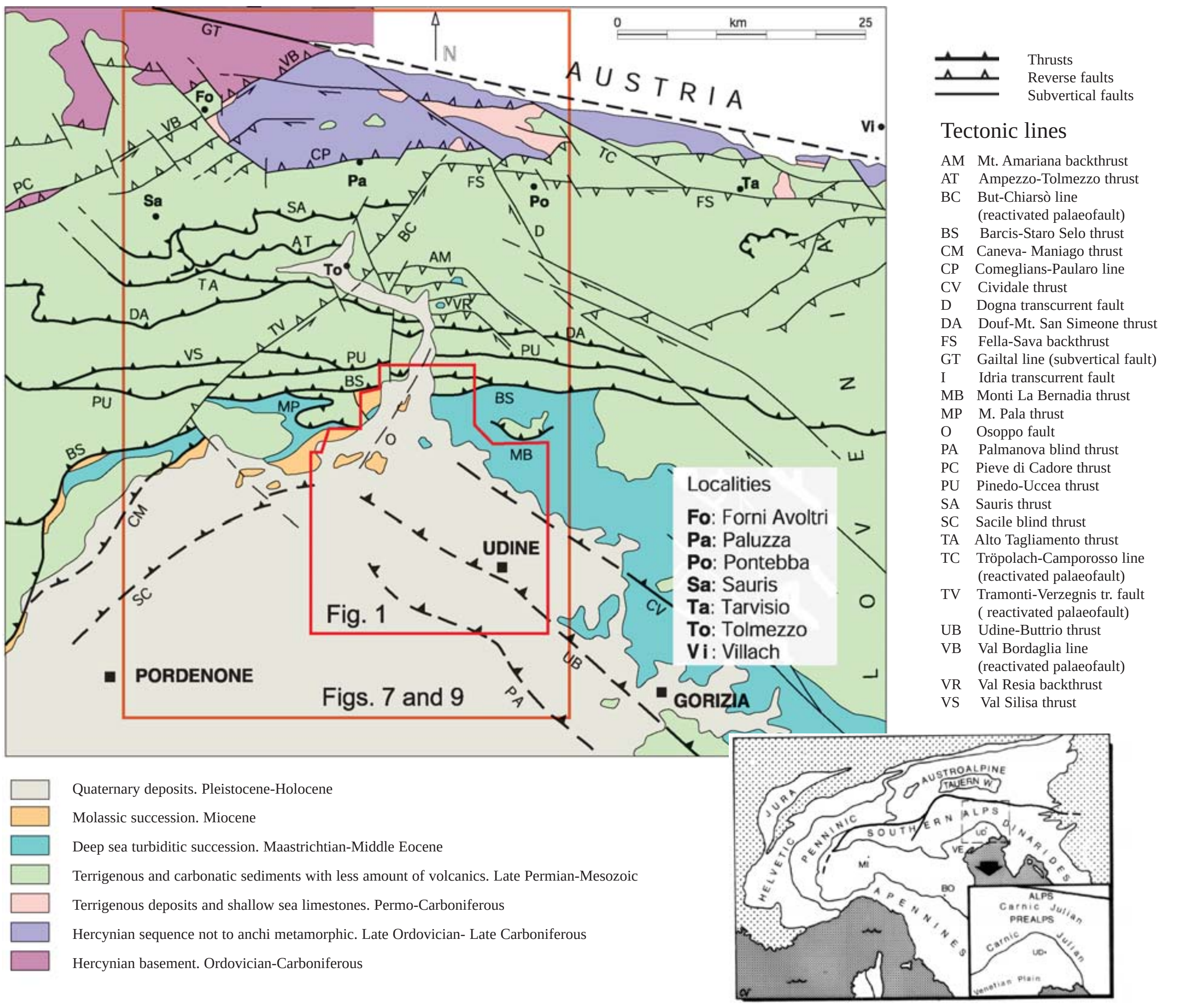


Fig. 2 - *Regional framework of the eastern Southern Alps. The Friuli reliefs are roughly made of south-verging tectonic slices overthrust mainly in Miocene times. In the eastern Southern Alps, from the inner (northern) to the outer (southern) belt, the outcropping succession becomes increasingly younger. More in detail, the innermost portion is made only of Palaeozoic rocks. On the opposite side, the Miocene succession is confined in the outermost part of the belt. That is a very important datum, as the composition of fluvial and glaciofluvial lithosomes is affected by the extent and position of the drainage areas, which have changed through time (after* VENTURINI et alii, *2001-2002).*

Three Neogene compression stages (Neoalpine phase) followed, due respectively to NE-SW (late Chattian-Burdigalian), N-S (middle-late Miocene) and NW-SE (Pliocene)-trending maximum stress (VENTURINI, 1991; CASTELLARIN *et alii*, 1992, 1996; LÄUFER, 1996).

Of these, the middle-late Miocene stage was that which produced the strongest shortening, that was responsible for the present structural setting of the thrust and fold belt.

At present, the core of the Carnic and Julian Fore-Alps is the most seismic area in the central and eastern Southern Alps, with the main activity occurring close to the relief margin, near the villages of Gemona and Venzone (BRESSAN *et alii*, 2003).

Approaching Udine from the south, the outer reliefs of the Carnic and Julian Alps appear to rise

Fig. 3 - *The Tagliamento braided riverbed as it appears from the top of the Aonedis N section. The 60 m high erosional scarp is interpreted as the deep entrenchment of the Torrent Arzino during the late glacial stage.*

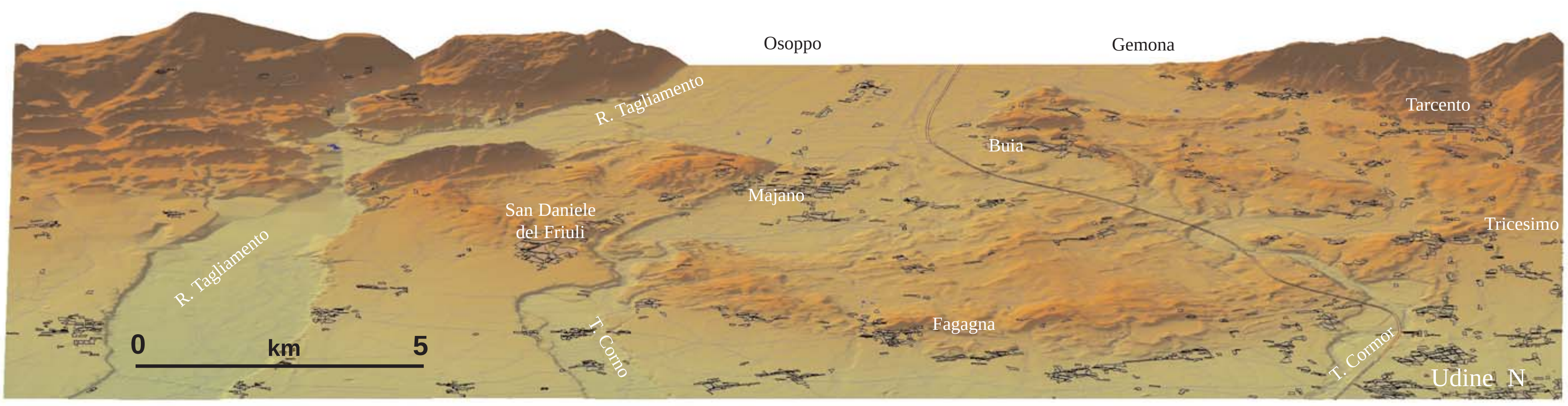


Fig. 4 - *3D surface map of the Tagliamento Moraine Amphitheatre. The highest and outermost moraine hills are rise about 150 m above the plain surface. Vertical exaggeration 12.43x. Lighting position angles: azimuth -127°; zenith 42°. View: field of view 45°, rotation 1°, tilt 49°; perspective projection.*

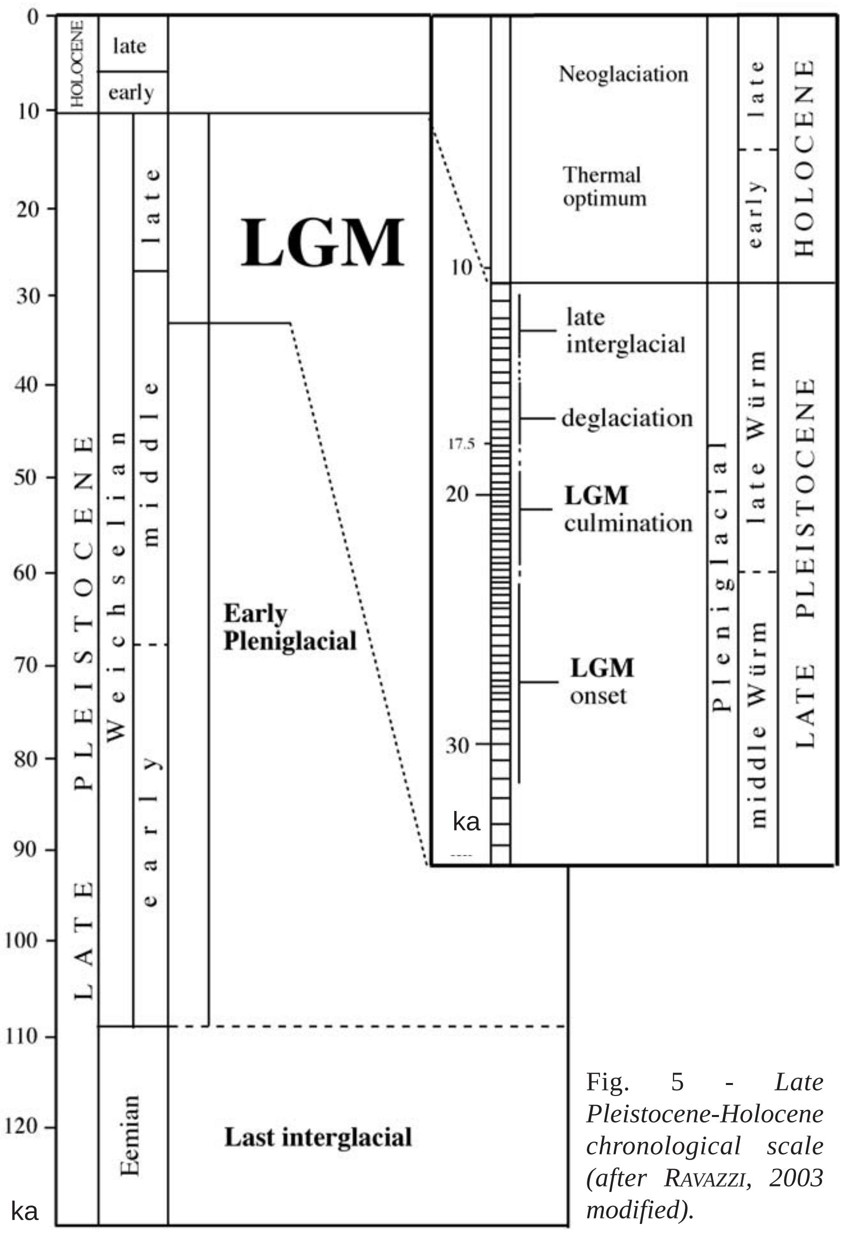


Fig. 5 - *Late Pleistocene-Holocene chronological scale (after* RAVAZZI*, 2003 modified).*

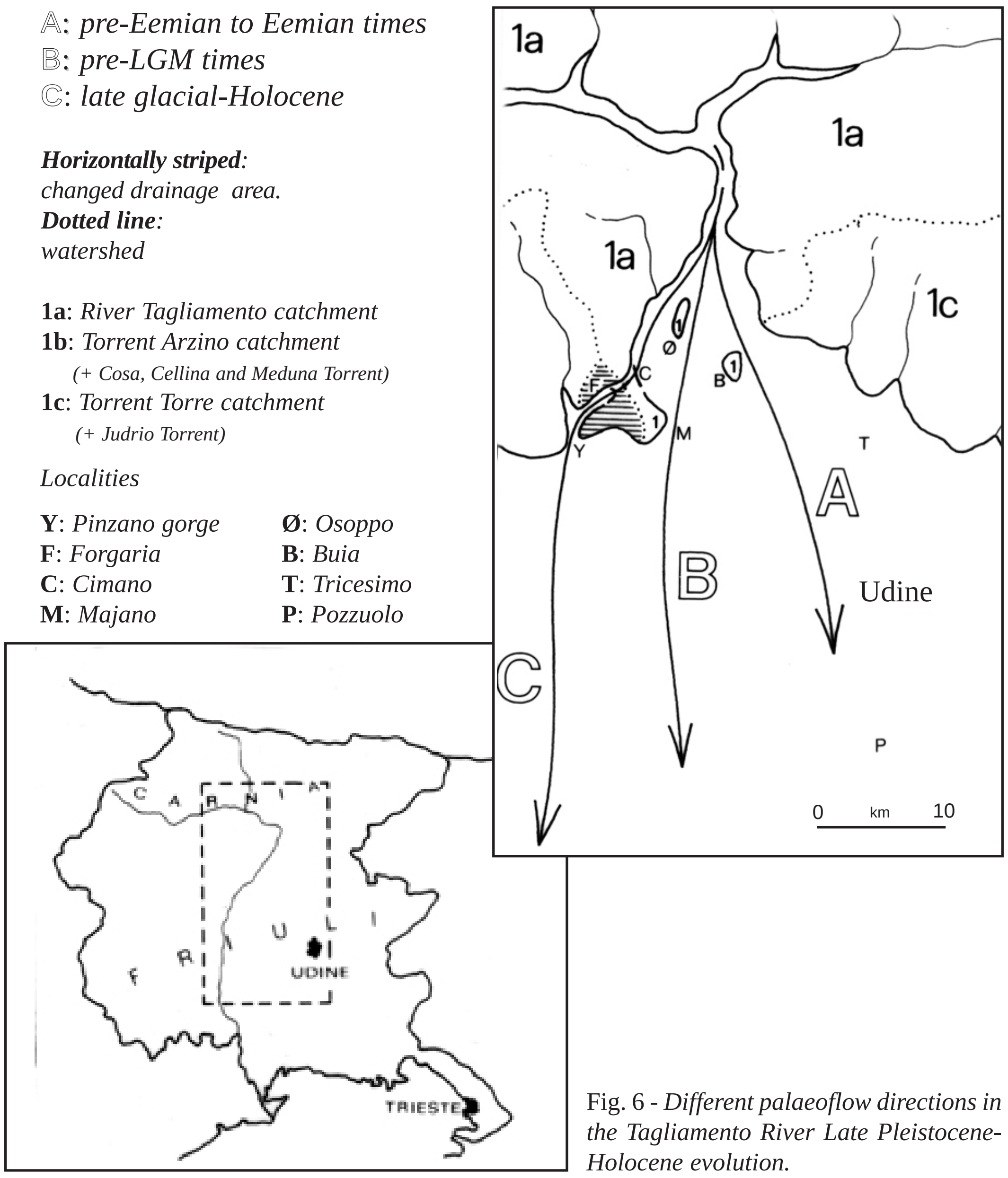


Fig. 6 - *Different palaeoflow directions in the Tagliamento River Late Pleistocene-Holocene evolution.*

abruptly from the Late Pleistocene plain and the Tagliamento Moraine Amphiteatre (last pleniglacial). A few km south of Udine, the outermost front of the Alpine belt is buried under Upper Pleistocene glaciofluvial gravels, and is marked by very gentle morphological uplifts due to the activity of a NW-SE-trending thrust system (PIERI & GROPPI, 1981; CATI *et alii*, 1987; FANTONI *et alii*, 2002; MERLINI *et alii*, 2002).

LATE QUATERNARY EVOLUTION

The Late Quaternary evolution of the central Friuli area is generated from the interaction between climate fluctuations, erosional and depositional processes, active tectonics and - last but not least - the inherited morphology on which all these factors have been active. The present-day landscape of the study area is characterised by the wide gravelly Tagliamento riverbed, deeply entrenched in glaciofluvial and fluvial deposits (Fig. 3), and by a remarkable moraine amphitheatre (Fig. 4).

The former stored up over a time span from > 36 ka BP to about 18 ka BP, while the latter was built during the Alpine Last Glacial Maximum, ALGM sensu RAVAZZI (2003), in short LGM (Fig. 5).

Prior to the LGM culmination, the drainage network of central Friuli differed from the present one (VENTURINI, 2003; ASTORI & VENTURINI, in progress), mainly in the independence of the Arzino Torrent catchment from the Tagliamento River-system (Fig. 6).

These now flow together across the Pinzano gorge (Y), while prior to the Late Pleistocene, a relief located north-west of the village of Cimano (C) represented the watershed between the Arzino and Tagliamento catchments. As a consequence, in Pleistocene times it was the Torrent Arzino (with the Cellina-Meduna streams) that accumulated gravels and sands in the western sector of the Friuli upper plain. On the opposite side, the River Tagliamento was the fluvial distributor for the central and eastern sectors of the upper plain.

According to literature (SACCO, 1939; GORTANI, 1959; MARTINIS, 1977; CARRARO & PETRUCCI, 1979; ZANFERRARI *et alii*, 1982; CAVALLIN *et alii*, 1987) and several unpublished data, recorded in Fig. 1 (ASTORI & VENTURINI, in progress), the Late Pleistocene-Holocene evolution of the area can be summed up as follows.

Pre-Eemian to Eemian times

In pre-Eemian times the Tagliamento ice snout reached the Friuli upper plain. The only remnants of it are confined at the top of the "Pozzuolo high", south of Udine (Fig. 7a). These consist of glaciofluvial gravels (VENTURINI, 1987), and also include elements of Australpine amphybolites and slightly metamorphosed porphirytes (FONTANA, 1999) and scattered boulders (?till) covered by very mature soil (FERUGLIO, 1929). The thickness of the soil is 2-2.5 m (up to 4 m in places) and the remaining cobbles are deeply altered.

The lack of younger sediments at the top of the "Pozzuolo high" is due to the Late Pleistocene active tectonics of the Palmanova line, which uplifted the Pozzuolo (P) area up to 12 m above the plain surface (Fig. 1). During the Eemian stage (last interglacial, *sensu* RAVAZZI, 2003), the retreat and disappearance of the ice tongue left some lacustrine deposits south of the Buia village (B). Here the thermoluminescence dating carried out on fluviolacustrine silty sands at depths of 13.65 m and 19.60 m gave an age of about 110±16.5 ka BP (SIROVICH, 1998). The cartoon shown, illustrating the situation (Fig. 7a), is highly speculative.

The pre-Last Glacial Maximum (pre-LGM)

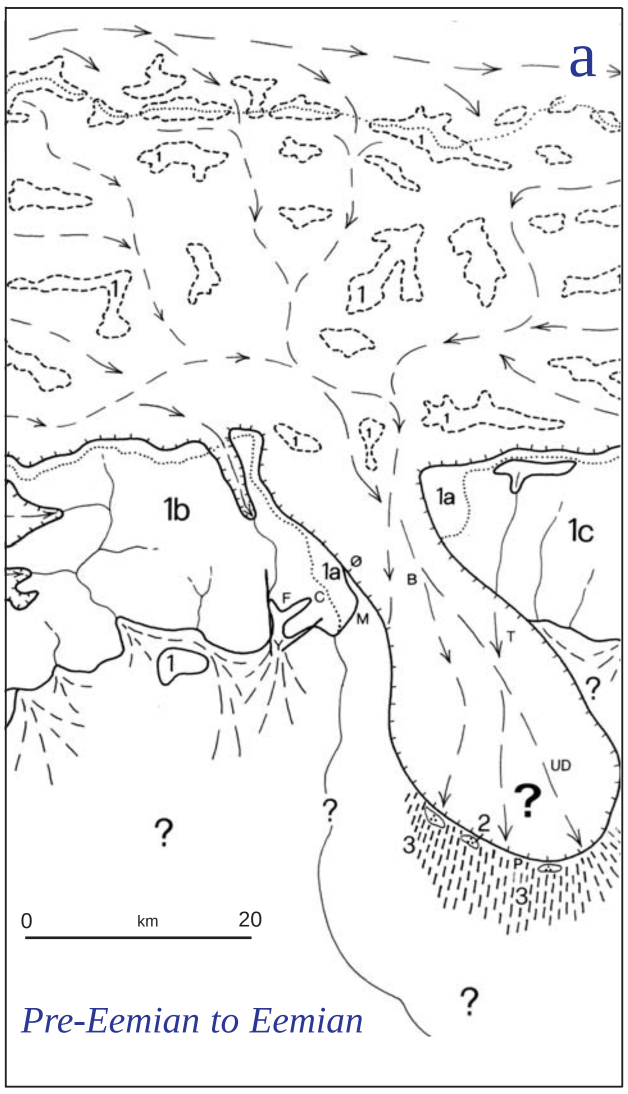
In pre-LGM times (early-middle Würm *Auct.*), once more the Tagliamento glacier reached the upper Friuli plain, spreading for a few kilometres south of Udine (TARAMELLI, 1874; COMEL, 1955, 1962; VENTURINI, 1988). The southern ice front stopped against the structural high (Fig. 7b) of the Pozzuolo area (P), as shown by the lack of relative deposits above the uplifted ridge (FONTANA, 1999).

At present, most of the relevant lodgement tills are buried under a few to several meters of glaciofluvial and fluvial gravels and sands, interpreted here as being pre-LGM in age (Fig. 7c).

During the Late Pleistocene (post-Eemian), the Tagliamento (-Fella) glacier extended over a large area including the main part of both the Carnic and Julian Alps. In the Arzino Torrent catchment (Fig. 7c), the glacial tongue was not long enough to reach the plain. The upper plain was only reached by the Tagliamento (-Fella) ice snout, while fluvial processes acted along the Arzino, Cosa and Meduna valleys (Fig. 7c) no moraines being found along their lower reaches (TARAMELLI, 1874; FERUGLIO, 1929).

In pre-LGM times, the Tagliamento ice snout left some of the tills both south and north of Udine (Figs. 8a,b). Data from digs and water drillings (COMEL, 1962; STEFANINI, 1986; PARONUZZI, 1988; VENTURINI, 1988) attest that tills are present only in the eastern part of the uppermost Friuli plain, proving that the ice lobe moved toward SSE without covering the estern sector.

This could be due to the fact that the Buia-Udine area might be a topographic low in pre-LGM times (GIORGETTI & STEFANINI, 1989). At that time, the Tagliamento-Arzino watershed (Fig. 7c) was still located along the Cimano ridge (C), a few km north-east of the Pinzano gorge (Y). The Cimano ridge was made of vertical Miocene sandstones jointing the Carnic Fore-Alps with the Majano Miocene hills (VENTURINI, 2003; ASTORI



Figs. 7a, b, c - *The cartoons summarize the Late Pleistocene-early Holocene evolution of the central Friuli Region. The numbers refer to the stratigraphic succession represented in the legend of Fig. 1.*

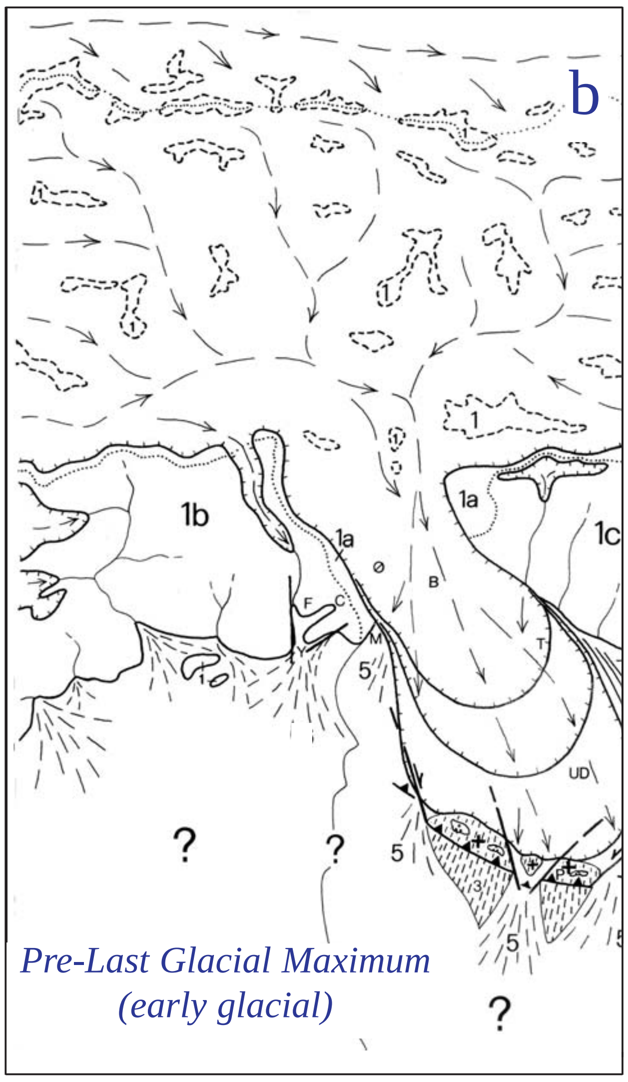
Localities

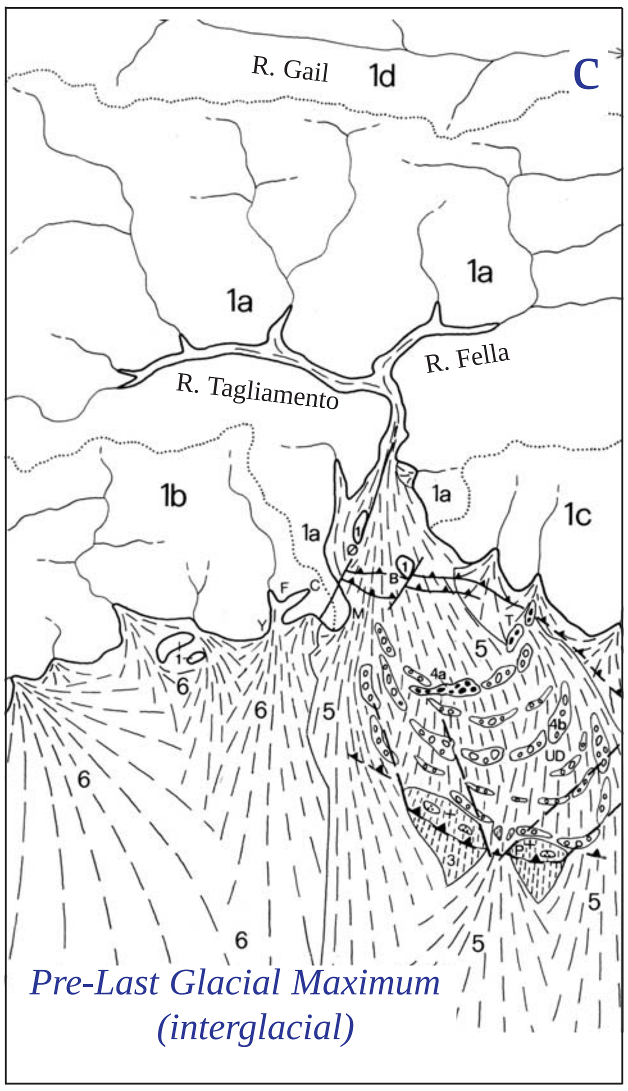
Y: *Pinzano gorge*
F: *Forgaria*
C: *Cimano*
M: *Majano*
Ø: *Osoppo*
B: *Buia*
T: *Tricesimo*
P: *Pozzuolo*

1a: *Tagliamento River catchment*
1b: *Arzino Torrent catchment*
(+ Cosa, Cellina and Meduna Torrent)
1c: *Torre Torrent catchment* *(+ Judrio Torrent)*
1d: *Gail River catchment*
(Black Sea 1st order hydrographic basin)

Symbols not present in the Legend of Fig. 1

?: *not in outcrop or not defined interpretation*
+: *morphotectonic high (from 4 to 12 m)*
Continuous lines: *reliefs boundary*
C. lines with small barbs: *glacier and snout contour*
Dashed arrows: *ice flows*
Thick dashed lines: *bedrock reliefs emerging from ice*





& Venturini, in progress). It was broken up later on by the coupled action of tectonics (Osoppo faults) and LGM ice. At present, the Cimano ridge remnants only crop out in the middle of the Tagliamento River corridor, partly buried under late glacial lacustrine and Holocene fluvial sediments (Figs. 1 and 7c).

Before the LGM onset, a fluctuating warm stage took place (Ravazzi, 2003). The ice retreat left the whole area under fluvial conditions. The upper part of the pre-LGM sedimentary record is well exposed along the eastern main scarp of the River Tagliamento (Aonedis N section, Fig. 10), and consists of channelized gravel bodies and alluvial plain sands and clays, with some palaeosoil horizons.

The lower part of the pre-LGM succession is ^{14}C age > 36 ka BP. The uppermost part of the pre-LGM succession is presumed to date from around 25,000 years ago, as it is covered by LGM glaciofluvial sediments. The pre-LGM gravels lack any evidence of Palaeozoic and Lower-Middle Triassic clasts, attesting that the conveyor at that time was not yet the Tagliamento River but the Arzino Torrent, as the Cimano ridge (C) was still the watershed between the two river-systems (Fig. 6). At the same time, in the eastern portion of the area (the Udine sector), the sedimentation of the Tagliamento (-Fella) catchment partly or totally covered the pre LGM- tills.

The Last Glacial Maximum (LGM)

During the LGM stage, the Tagliamento glacier once more reached the upper plain (Fig. 7d). The ice snout stopped a few km north of Udine, laying down a continuous arc-shaped terminal moraine (Fig. 4) between the Carnic Fore-Alps (Forgaria, F) and the Julian Fore-Alps (Tricesimo, T).

The frontal and southern moraine ridge, which is up to 200 m thick, is the main feature of the Tagliamento Moraine Amphitheatre (Gortani, 1959). Pulses occurring in the Tagliamento ice snout produced a set of recessional moraine arcs (Croce & Vaia, 1986; Sgobino, 1992). The Cimano ridge (C) experienced fracturing due to the activity of the Osoppo fault system (Giorgetti *et alii*, 1995) and was erased by the Tagliamento glacier.

The ice front was right behind the Pinzano gorge (Y), at Forgaria (F). On the eastern side, in the Tricesimo (T) area, the glacial drift (LGM) onlapped the innermost among the pre-LGM moraines, which are still partly exposed (Figs. 1 and 9a).

At the front of the LGM terminal moraine arc, the main meltwater streams spread out gravels and sandy gravels (thickness >30 m) which built an outwash plain (sandur).

These outwash sediments are mainly confined in the western side of the amphitheatre. Indeed, as shown in Fig. 1, the outwash fans are best developed in the western area, as this is where the widest meltwater streams were located (Comel, 1955).

Evidence is also given in the microrelief map that

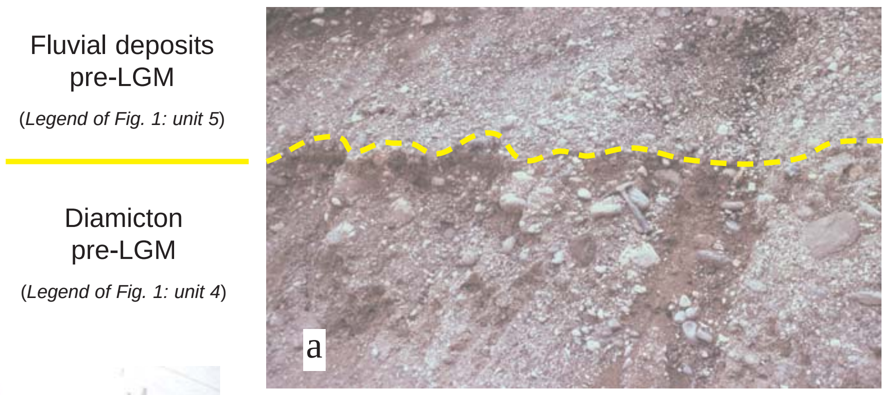


Fig. 8 -
a) *Dig opened in the village of Colugna (2 km NW of Udine, close to the Torrent Cormor) in 2002. The stratigraphic profile shows the glaciofluvial deposits of the outwash plain (pre-LGM) onlapping a pre-LGM mud-rich diamicton with >1 m boulders, not visible in the photo. See also Fig. 7c.*
b) - *Some boulders dug out SW of Udine in 1987 during the construction of the highway. These are similar to those dug out in the village of Colugna (Fig. 8a) and in many areas of the eastern Friuli upper plain.*

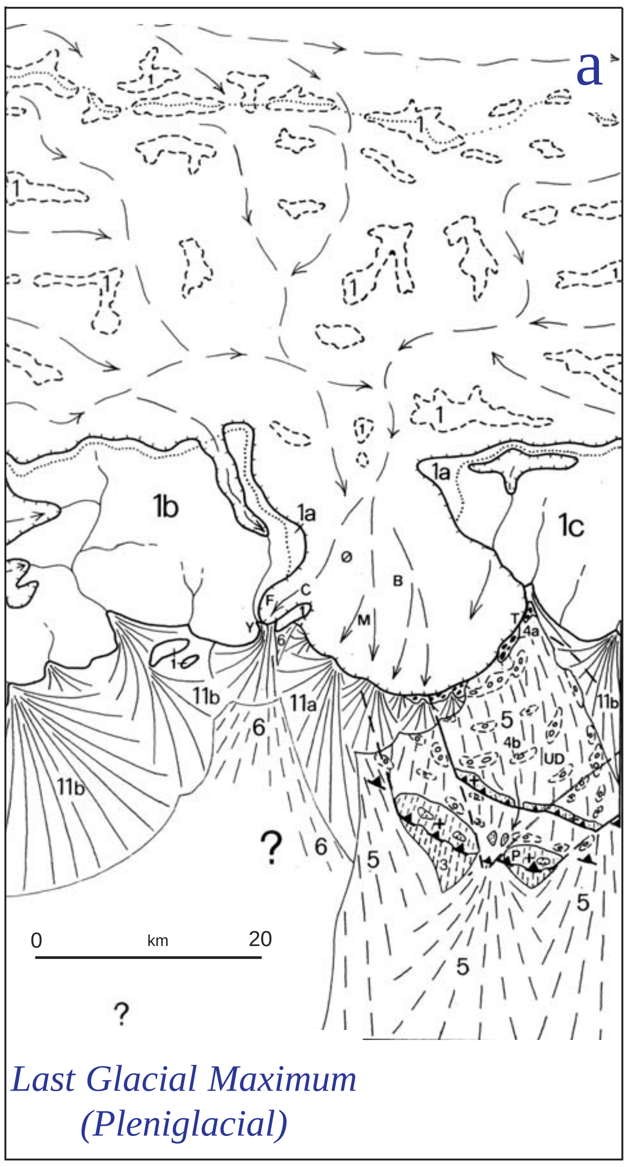
displays in the western sector of the proglacial plain a regular flat surface that is peculiar to outwash plains (Fig. 19), and an irregular surface in the eastern sector, resulting from an older moraine which was not completely covered by the subsequent pre-LGM glaciofluvial deposits (Fig. 20).
The morphology of the glaciofluvial deposits of the eastern area (Fig. 11) is not consistent with a LGM age, as they stop northwards against the pre-LGM moraines (Fig. 1). The outwash deposits of the eastern area are therefore explained as being coeval with the pre-LGM tills which are located outside the LGM moraines.
The Meduna-Cellina river-system, to the west of the Tagliamento Moraine Amphitheatre, and the Natisone-Torre river-system to its east, laid down large amounts of fluvial sediments. In places, they onlap the pre-LGM glaciofluvial sediments and partially interfinger with the LGM outwash plain (sandur) deposits.
The LGM glaciofluvial succession crops out in spectacular fashion in the Aonedis N section (Fig. 10). The LGM gravels rest with gentle erosional contact upon the underlying pre-LGM sands and gravels. The glaciofluvial sediments have some 2-3% content of Palaeozoic and Lower-Middle Triassic clasts, reflecting the dismantling of the northernmost reliefs of the Tagliamento catchment.
As seen, during LMG the meltwater streams fed the area in front of the western terminal moraine arc, forming a smooth pro-glacial plain (outwash plain). Otherwise, in the area comprised between Udine and the eastern moraine amphitheatre, the uniform flat and gently dipping surface peculiar of the outwash plain is missing (Figs. 11 and 20).
The lack of main meltwater streams has preserved the irregular pre-LGM morphology.

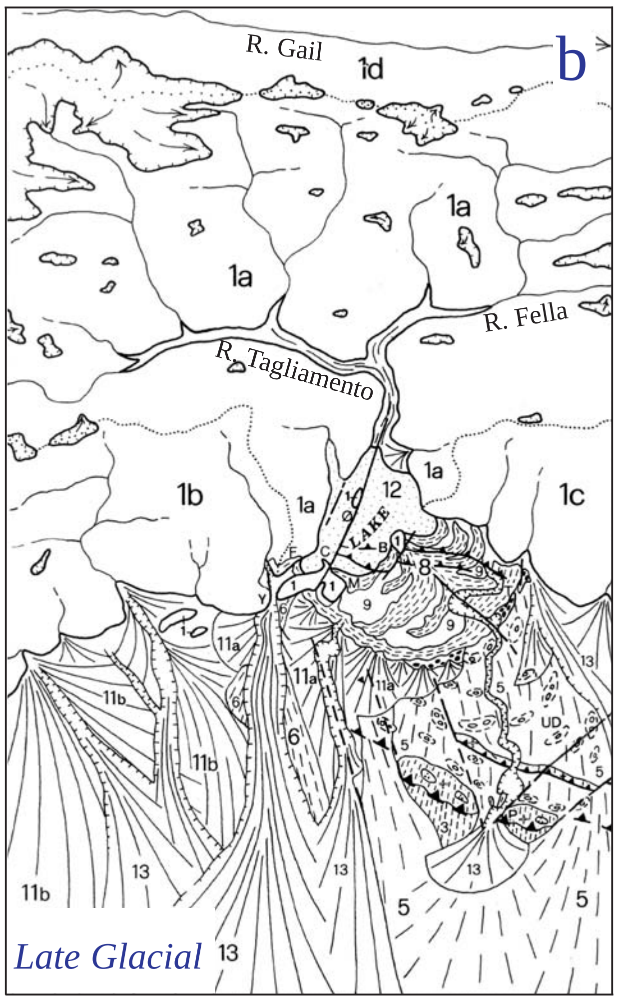
The deglaciation and the glacial stage

During the Alpine deglaciation, a wide lake formed between the retreating glacial lobe and the innermost moraine arc (FERUGLIO, 1929; STEFANINI, 1978, 1986; SGOBINO, 1992). Geophysical investigations (GIORGETTI & STEFANINI, 1989) record lacustrine deposits (Fig. 7e) all over a wide area around the village of Osoppo (Ø).
As the Osoppo palaeolake trapped the fluvial sediments, in central Friuli the upper plain accretion stopped. In the Forgaria (F) sector, the Torrent Arzino eroded part of the terminal moraine, entrenching the Upper Pleistocene plain deposits and forming scarps more than 60 m high. The same erosive processes were active along the Corno and Cormor fluvial corridors (Fig. 9b).
During a time span ranging from the Late Pleistocene (LGM onset) to Holocene times, the Friuli upper plain experienced active tectonics.
The reactivation of the Udine-Buttrio line, born in Miocene times, gave rise to a NW-SE-trending narrow ridge, elevated up to 4 m above the average level bottom of the surrounding plain, and located a few km south of Udine.
The morphostructural ridge uplifted the glaciofluvial pre-LGM deposits and was cut in antecedence by the Cormor Torrent (Fig. 9b).
During early Holocene times, the moraine arc of the Forgaria (F) sector -located in the eastern portion of the moraine amphitheatre, and against which the water stopped forming the Osoppo palaeolake- fell in.
The River Tagliamento flowed through the opening and became the main stream crossing the Pinzano gorge (Y). Downstream from the gorge, the riverbed widened to form the present day Tagliamento River corridor.

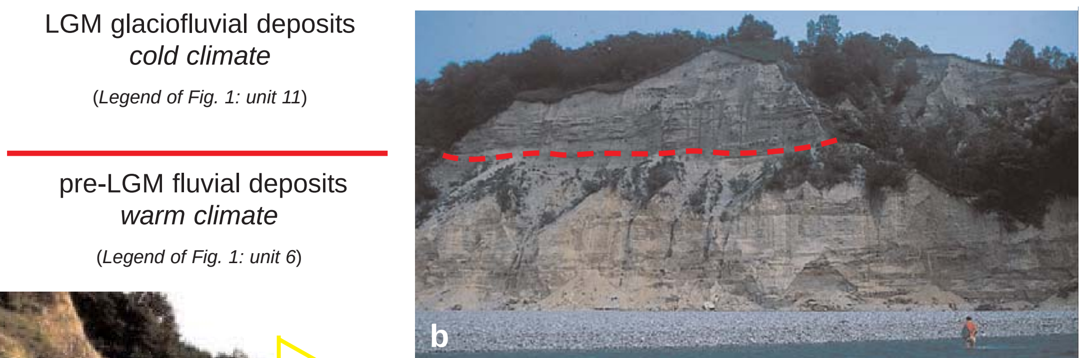
DIGITAL TOPOGRAPHY METHODOLOGY

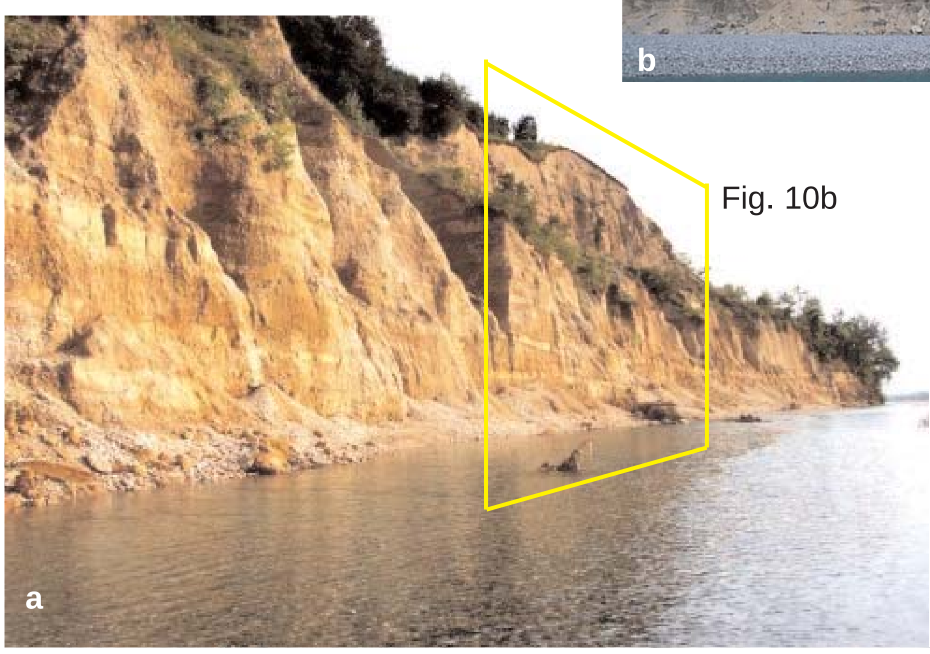
Digital representations of the Earth's surface and related computer-assisted analyses are increasingly used not only in geosciences but also in land management and planning. Digital models of the Earth differ depending on the purpose they are generated for. Digital Surface Models (DSM) are used to represent the terrain, including vegetation, buildings, roads, etc., while Digital Elevation Models (DEM) represent the real ground surface (relief), and only spot heights are stored in them. DEMs are very useful tools for geomorphological and geological analysis and interpretation, as they only show ground surface elevation, excluding man-made objects.
The integrated study of several DEM-derived maps (shaded relief, 3D, microrelief) has allowed a better interpretation of the surface morphology of central Friuli, providing an essential support to the classic geological approach based on field survey (Figs. 11, 12 and 13). The digital representations shown here are derived from the digital technical map (CTRN) of the Region Friuli Venezia Giulia.
The mapping software packages used were





Figs. 9a, b - *The cartoons summarize the Late Pleistocene-early Holocene evolution of the central Friuli Region. The numbers refer to the stratigraphic succession represented in the legend of Fig. 1.*
Symbols not present in the legend of Fig. 1 are in Fig. 7.





Figs. 10a, b - *The well-exposed Aonedis N section. 1 km south of the Pinzano gorge, the present Tagliamento River scarp (left side) cuts the pre-LGM fluvial sands, gravels and conglomerates (25 m), covered with LGM glaciofluvial gravels and conglomerates (30 m). The two lithosomes are quite distinguishable by their colour; moreover, the younger lithosome is the only one with Palaeozoic and Lower Triassic clasts (ca. 2-3% of total).*

ArcView® GIS 3.2 (ESRI, Redlands, CA) and ENVI® 3.5 (Research Systems, Boulder, CO).

A preliminary dataset was created by extracting spot heights from the CTRN database; this was supplemented with data derived by converting original CTRN contours (where present) into points. From this dataset, a first series comprising a rough microrelief map, a three-dimensional (3D) map and a shaded relief map, was generated. A simple visual analysis allowed man-made objects (roads, railways, etc) to be quickly singled out, so that the spot heights located on them could be promptly removed. The final dataset contains 298 points/km², and a 25 m-spacing square grid was built using the triangulation with linear interpolation method (Delaunay triangulation). This is the input grid used to generate several visualisations of the DEM, in which only the relief is portrayed.

A shaded relief map (Fig. 13) is an image of the ground surface as it would look if it were made of an ideal homogeneous material, with the sun illuminating it from a given position. In order to investigate the study area, particular features of the surface were brought out on the shaded relief map by changing the direction of the light source (azimuth and altitude) and increasing the vertical exaggeration factor (Fig. 15).

Besides several shaded relief representations, a simple visual analysis was also carried out on 3D maps (Figs. 12 and 16), which can be rotated and tilted, allowing the landforms to be scanned from all points of view (Fig. 17). Several colour settings were arranged in order to better highlight morphological features.

Of all those mentioned, the microrelief map is the most useful (Figs. 11, 19 and 20), as it displays the shape of the surface most accurately, the contour interval of 0.5 m allowing even the slightest landforms to be recognized.

Fig. 11 - *Microrelief map. The contour interval is 0.5 m. The contour lines are grouped in sets of ten and differently coloured. Red contours bound each set, highlighting the tens up to 280 m a.s.l., while beyond this value all the contour lines are red. Between the main red contours, light-blue lines mark the 5 m intervals up to 155 m a.s.l.*

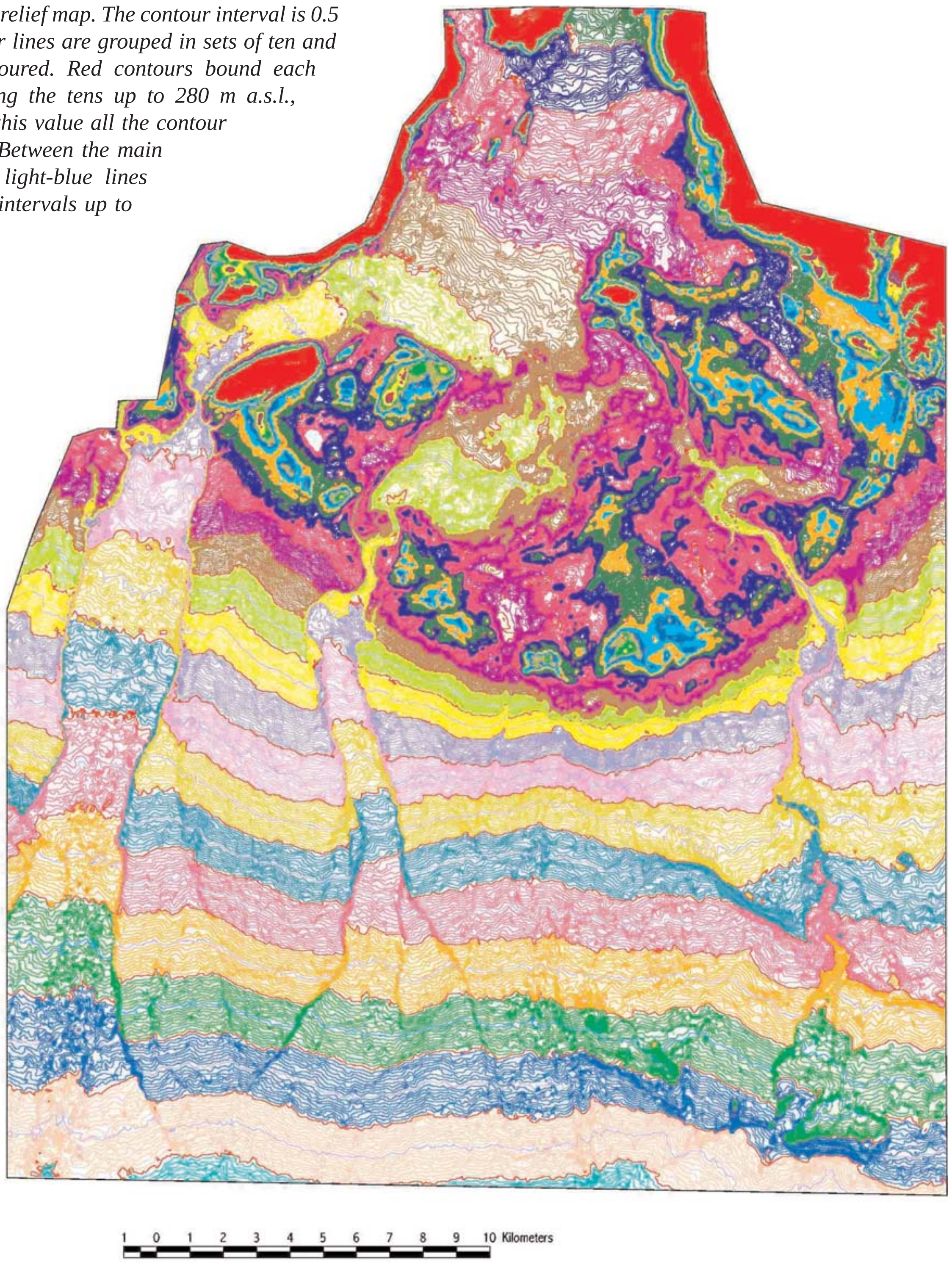
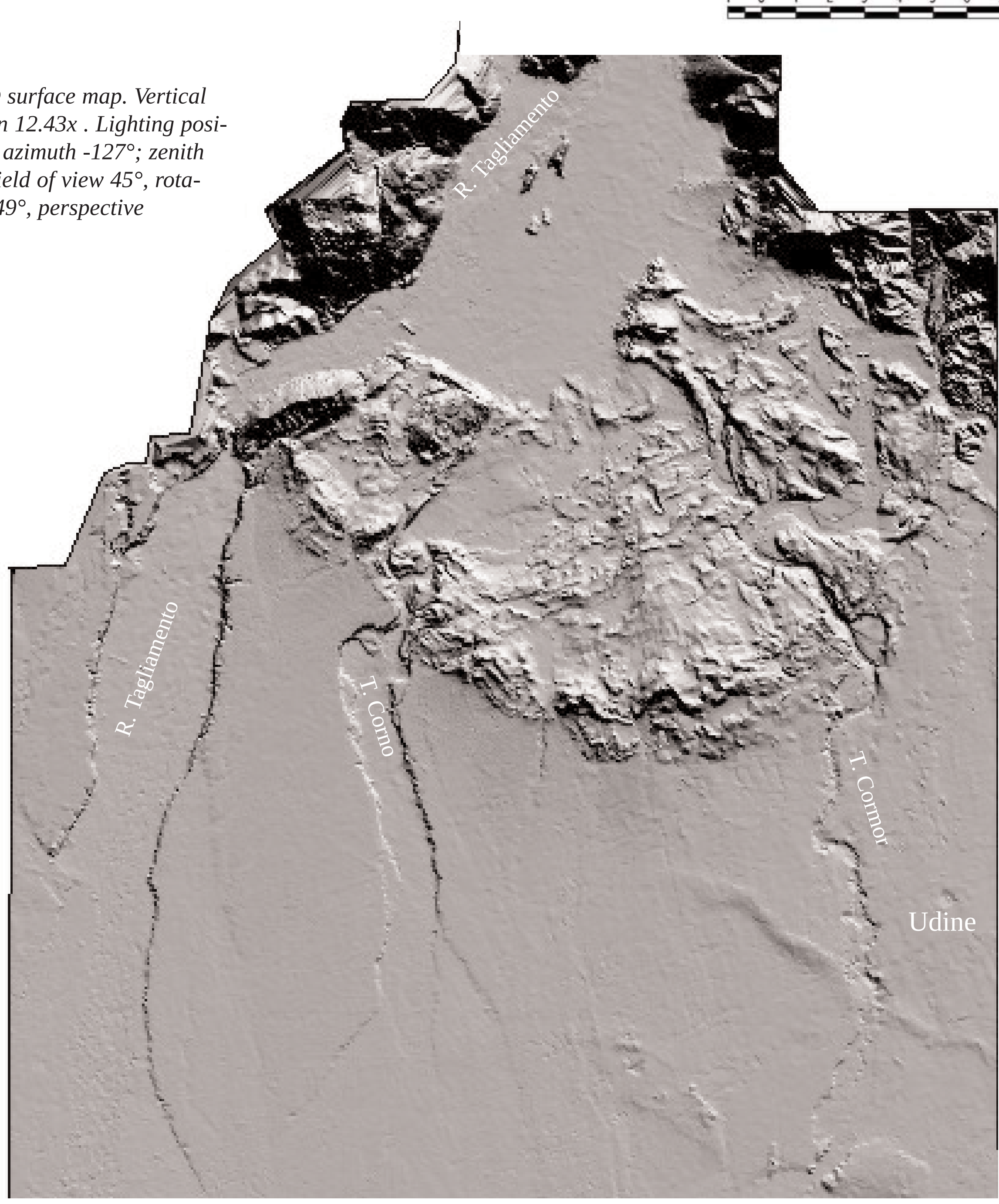


Fig. 12 - *3D surface map. Vertical exaggeration 12.43x . Lighting position angles: azimuth -127°; zenith 42°. View: field of view 45°, rotation 1°, tilt 49°, perspective projection.*



The analysis on this map was performed by changing the scale view, the colour settings and the topographic drawing profiles. At the end of this first analysis, field surveys were planned and carried out in order to check the preliminary outcomes.

The DEM interpretation results from the cross-analysis of all these maps, updated with the field surveys. The final geological interpretation is based on classic field survey data, integrated by the interpretation of the relevant DEM-derived maps.

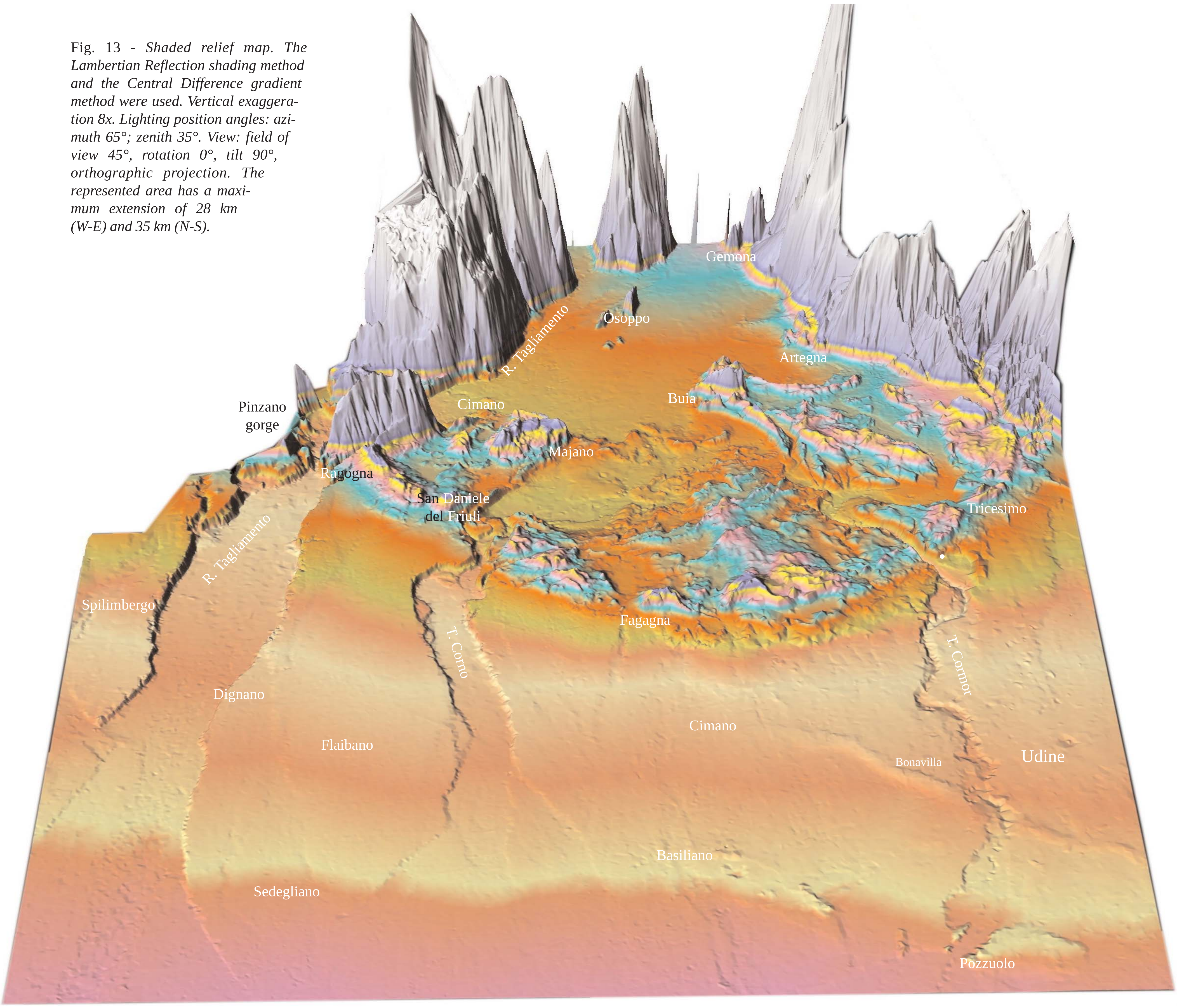
ACTIVE TECTONICS

The DEM-derived maps have been shown to be a useful tool to be used to detect recent deformations occurring in mainly non-coherent Quaternary deposits. Deformations are generally marked by ground ridges and/or confined depressions. However, very few ridges and depressions can be interpreted as tectonic evidences, and a wide spectrum analysis is required to confirm the DEM suggestions.

The DEM-derived maps provide information to be compared with field data and, where present, with geophysical prospectings, geoelectrical investigations, and so on. The relationships between deposits and erosions also enable the definition of the age of tectonic activity.

In the study area, two zones in particular are suitable for this purpose, as they show different and

Fig. 13 - *Shaded relief map. The Lambertian Reflection shading method and the Central Difference gradient method were used. Vertical exaggeration 8x. Lighting position angles: azimuth 65°; zenith 35°. View: field of view 45°, rotation 0°, tilt 90°, orthographic projection. The represented area has a maximum extension of 28 km (W-E) and 35 km (N-S).*



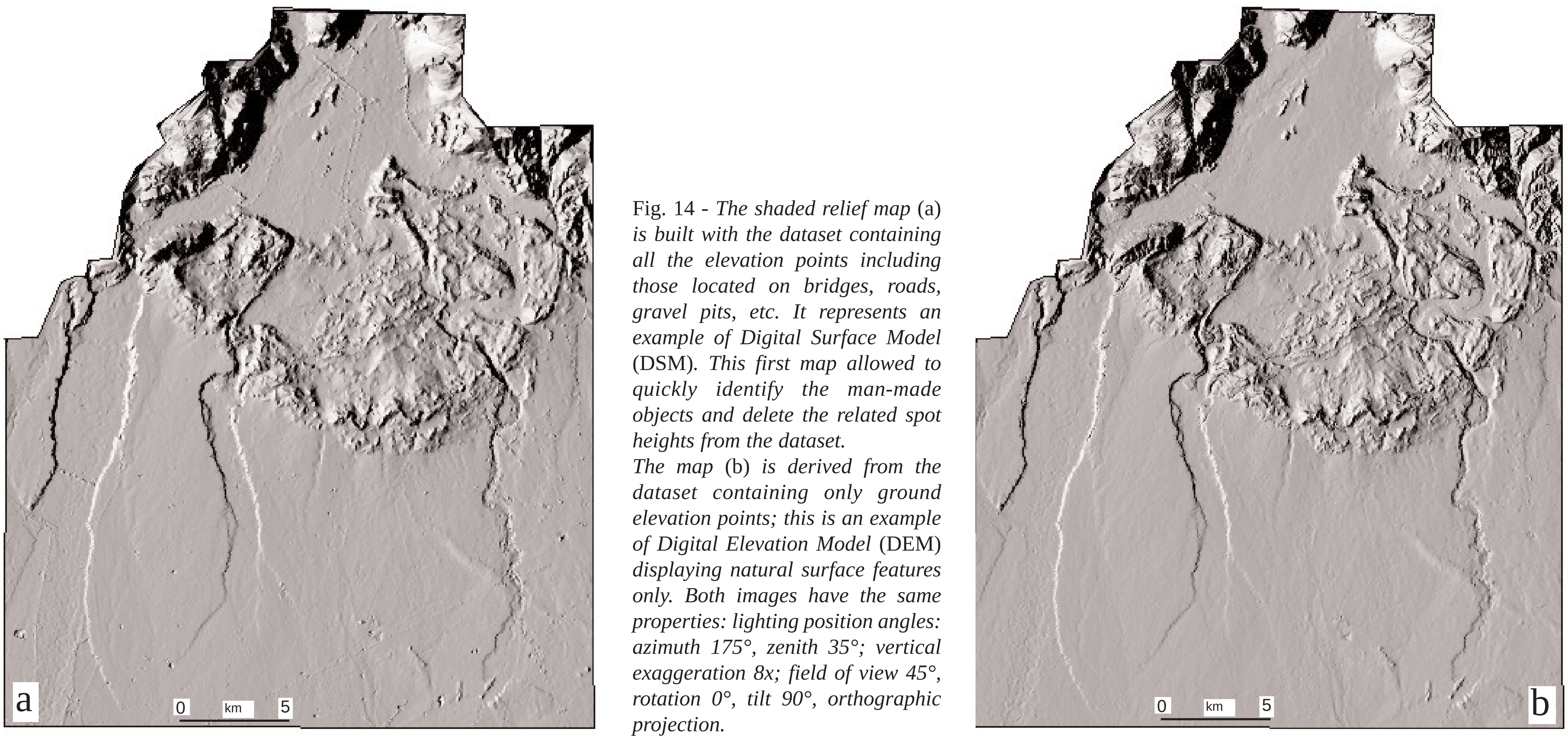
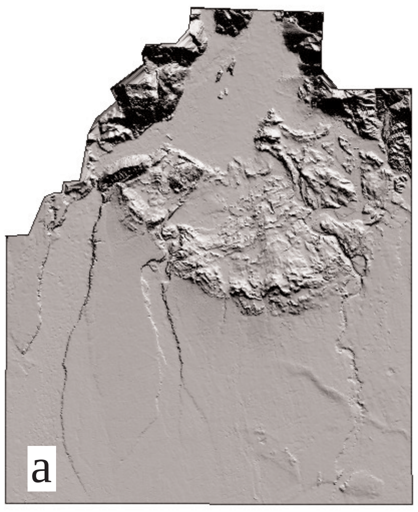
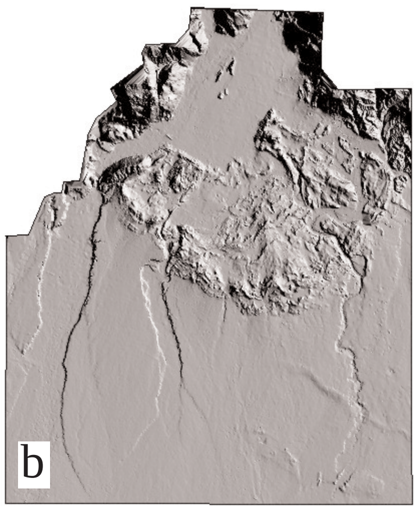


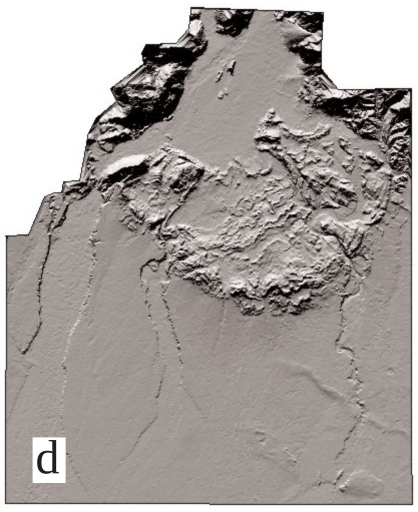
Fig. 14 - *The shaded relief map* (a) *is built with the dataset containing all the elevation points including those located on bridges, roads, gravel pits, etc. It represents an example of Digital Surface Model* (DSM). *This first map allowed to quickly identify the man-made objects and delete the related spot heights from the dataset.*
The map (b) *is derived from the dataset containing only ground elevation points; this is an example of Digital Elevation Model* (DEM) *displaying natural surface features only. Both images have the same properties: lighting position angles: azimuth 175°, zenith 35°; vertical exaggeration 8x; field of view 45°, rotation 0°, tilt 90°, orthographic projection.*



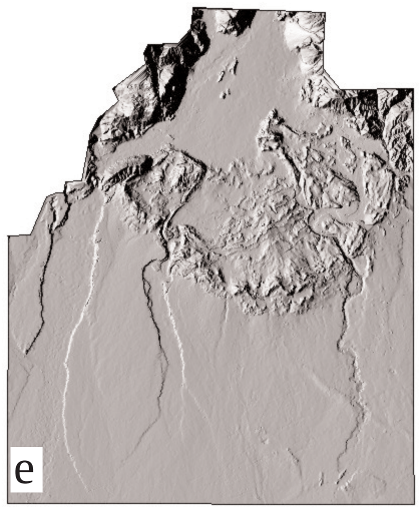
Lighting position angles: azimuth 65°; zenith 35°. Vertical exaggeration 8x.



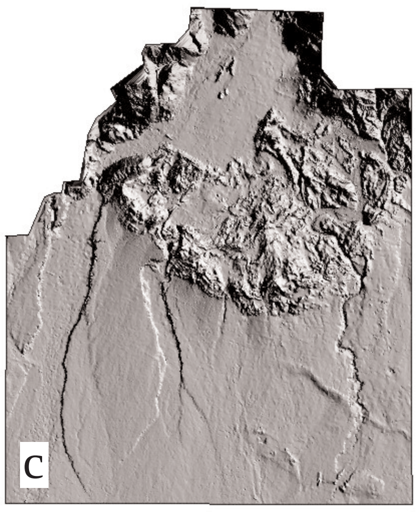
Lighting position angles: azimuth 21°; zenith 35°. Vertical exaggeration 8x.



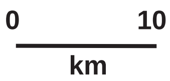
Lighting position angles: azimuth 100°; zenith 30°. Vertical exaggeration 8x.



Lighting position angles: azimuth 175°; zenith 35°. Vertical exaggeration 8x.

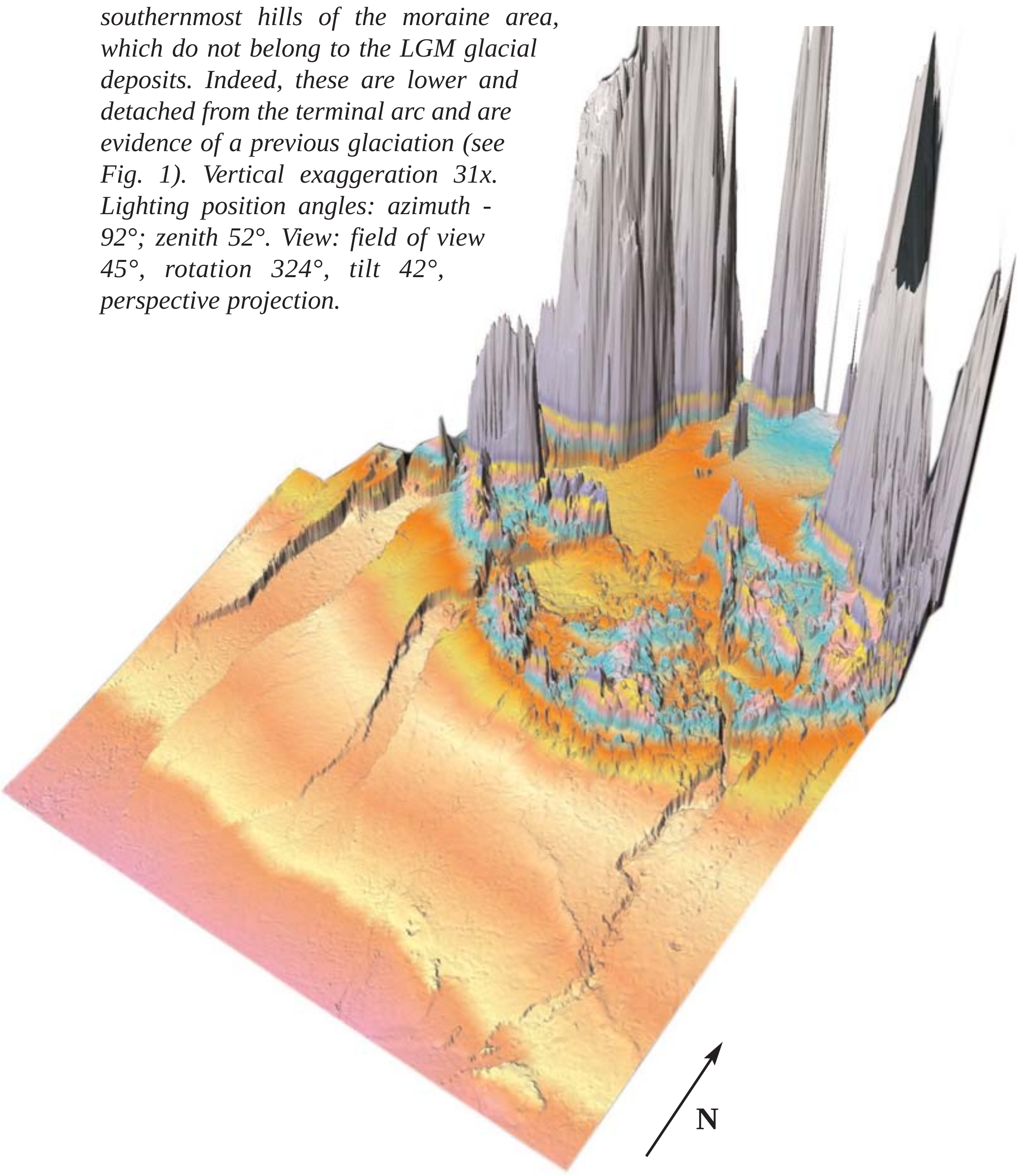


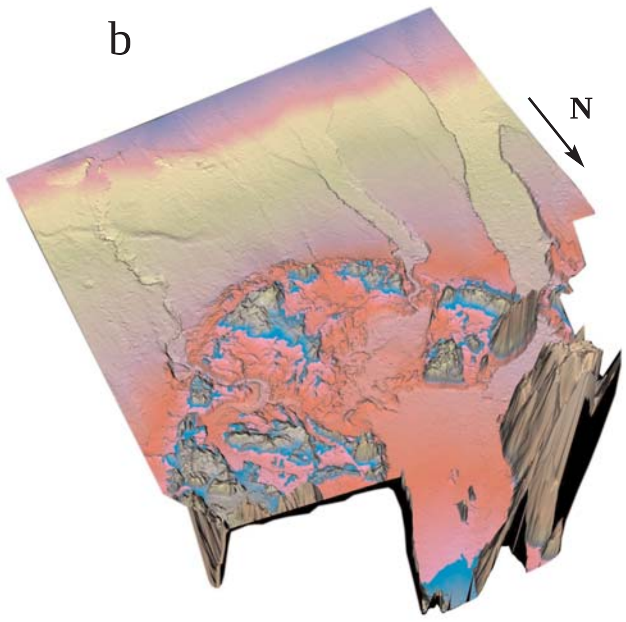
Lighting position angles: azimuth 21°; zenith 35°. Vertical exaggeration 20x.



Figs. 15a, b, c, d, e - *Different lighting angles bring out (or hide) surface features. In pictures* b) *and* c) *the effect of different vertical exaggeration can also be compared. The view is the same in all the maps (field of view 45°, rotation 0°, tilt 90°, orthographic projection).*

Fig. 16 - *Surface features are emphasised by increasing vertical exaggeration, as well as by varying surface colour gradation (compare to Figs. 13 and 17a). Note the surface south of the moraine amphitheatre among the riverbeds: on the left it is smooth (outwash plain), while on the right it is bumpy (sub-outcropping pre-LGM moraine). In this picture another peculiar feature is clearly displayed, that of the southernmost hills of the moraine area, which do not belong to the LGM glacial deposits. Indeed, these are lower and detached from the terminal arc and are evidence of a previous glaciation (see Fig. 1). Vertical exaggeration 31x. Lighting position angles: azimuth -92°; zenith 52°. View: field of view 45°, rotation 324°, tilt 42°, perspective projection.*





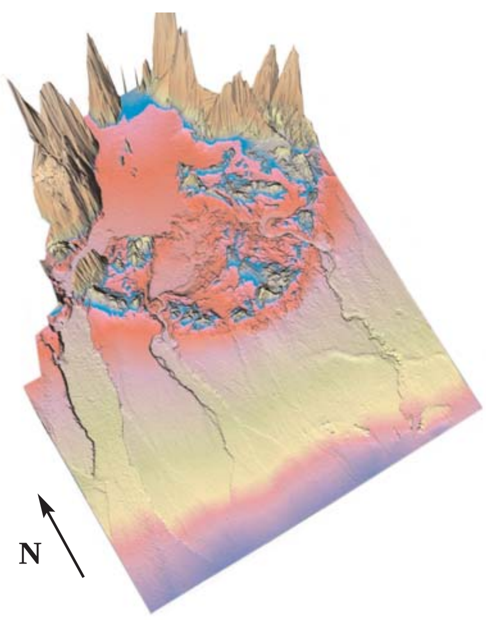


Fig. 17 - *Morphology can be better analysed by changing view properties and lighting. Vertical exaggeration is the same in both images (15x).*
a) *Lighting position angles: azimuth -132°; zenith 50°. View: field of view 45°, rotation 31°, tilt 77°, perspective projection.*
b) *Lighting position angles: azimuth 52°; zenith 60°. View: field of view 45°, rotation 208°, tilt 57°, perspective projection.*

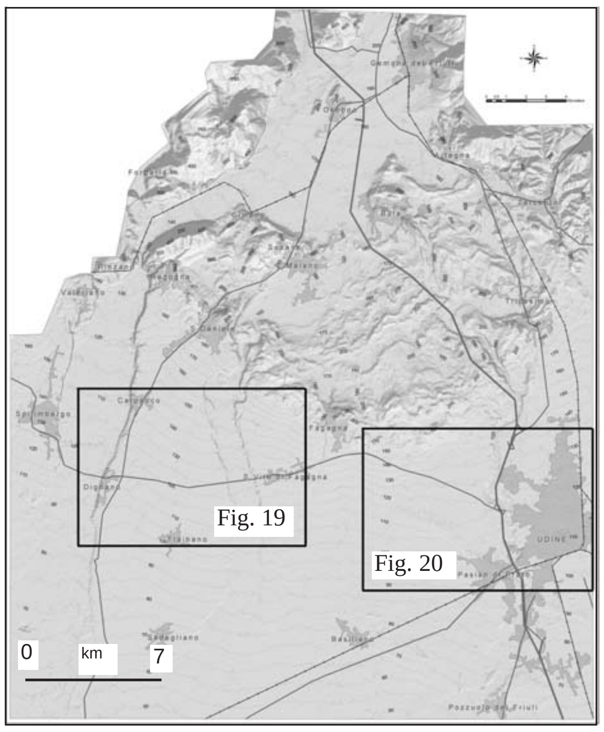


Fig. 18 - *Sketch map with location of Figs. 19 and 20, useful to compare the morphological features of two different areas of the Friuli upper plain, south of the moraine amphitheatre, by microrelief maps.*

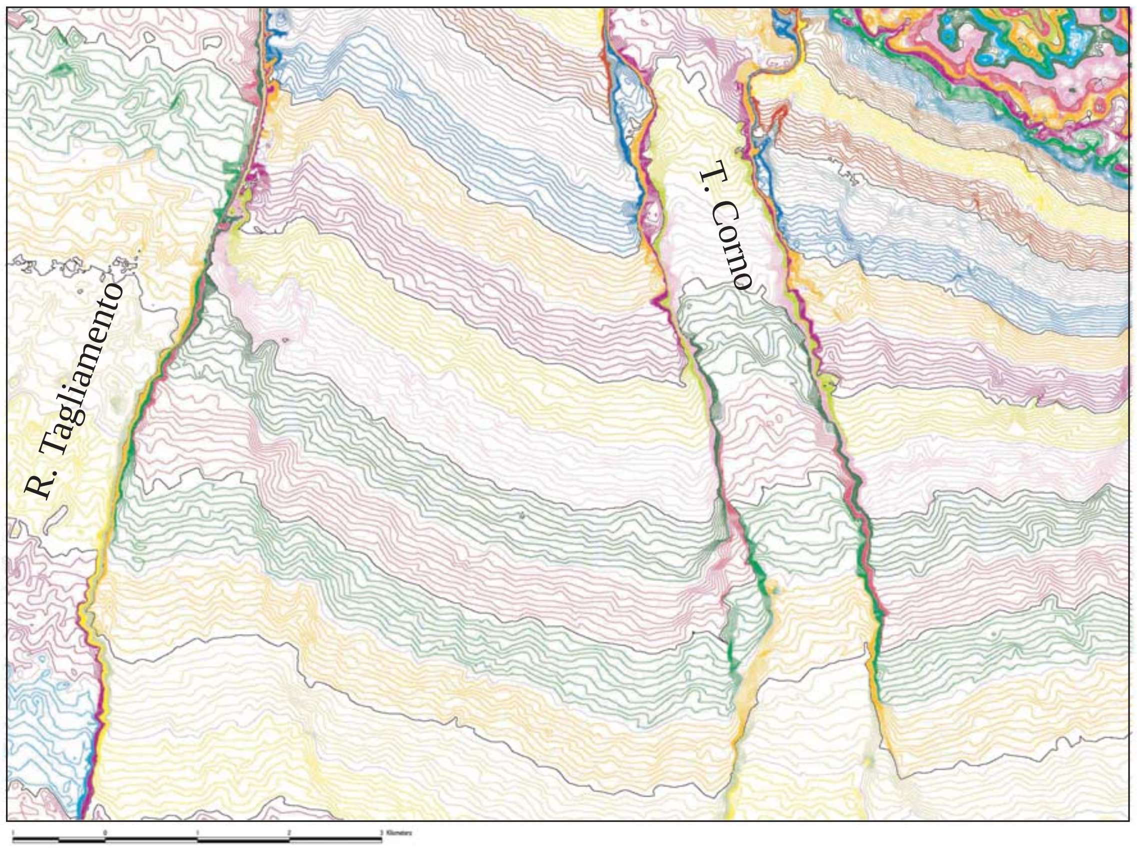


Fig. 19 - *The sector between the Tagliamento and Corno main scarps is a regular flat surface representing the LGM outwash plain. It is quite different with respect to the Cormor area situation (see Fig. 20).*

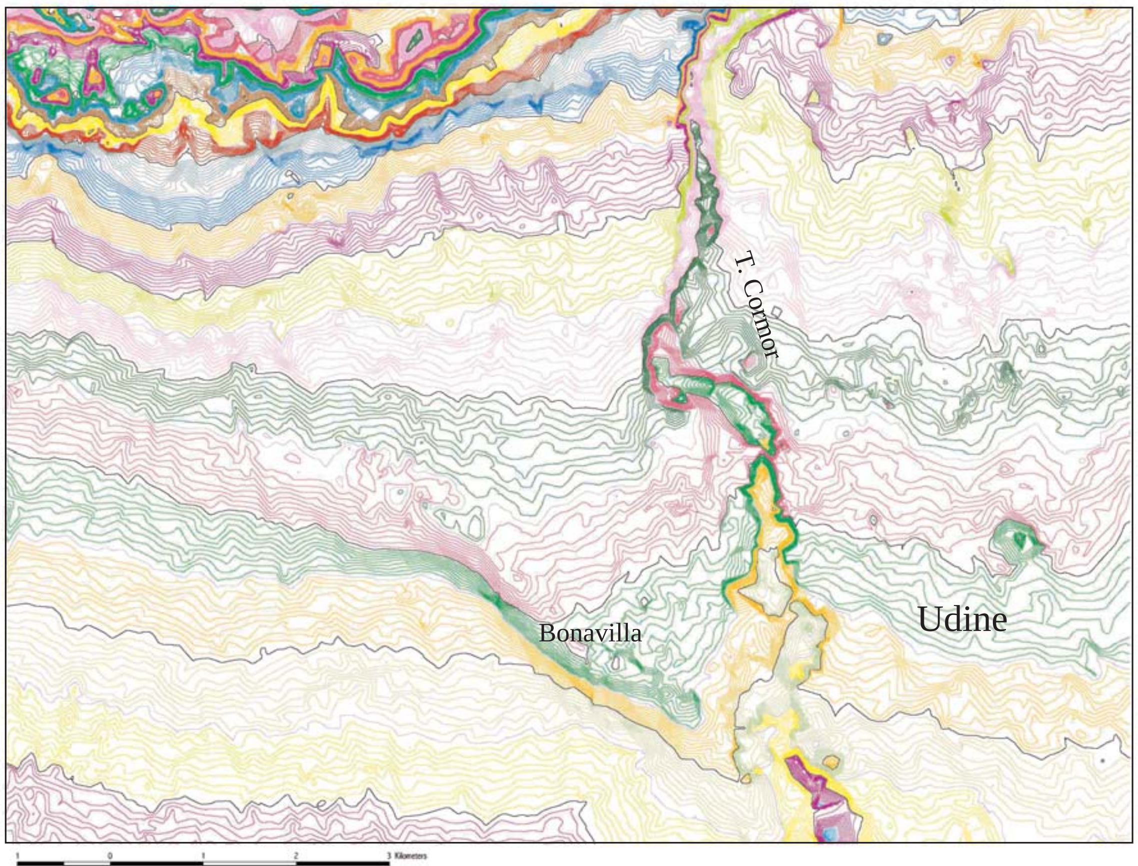


Fig. 20 - *In the Cormor area, surface irregularities increase moving eastwards and northwards. This area is evidence of a sub-outcropping, older moraine, not completely covered by the outwash deposits of meltwater streams related to the pre-LGM glaciation. LGM outwash plain deposits never interested this sector.*

prominent features which can be related to active tectonics. These are, respectively: a) the Tagliamento Moraine Amphitheatre and b) the eastern side of the Friuli upper plain.

a) *The Tagliamento Moraine Amphitheatre*

Again in this case the DEM-derived maps of the area (Fig. 22) are useful to enable the detection of a number of morphological features related to active tectonics.

In both the Majano area (M) and on the left riverside of the Torrent Cormor, south-west of Tricesimo (T), there are clear morphological evidences which can be speculatively thought of as being induced by recent (post-LGM) tectonics. Two vertical, NNE-SSW and NNW-SSE-trending fault systems seem to have produced sinkings of large square sectors of about 5-10 km^2 each.

As seen, digital maps are a very useful tool indeed for highlighting certain particular data sets (morphological trends and bounds, relationships among tectonic features and depositional bodies, …).

However, in order to be fully reliable, the DEM suggestion must fit in well with other different datasets, such as field and subsurface data.

The area in question is still under study.

b) *The eastern Friuli upper plain*

In the Friuli upper plain, geophysical prospectings (PIERI & GROPPI, 1981; FANTONI *et alii*, 2002) and stratigraphic data from drilled cores (STEFANINI, 1986; VENTURINI, 1987, 2002) have pointed out the presence of a buried thrust system (Figs. 1 and 23). This is N120°E trending and involves the Cenozoic and, partly, the Quaternary successions (Fig. 1).

Its main features are the Udine-Buttrio and the Palmanova lines. The presence of two narrow uplifted areas a few km south of Udine, elevated between 4 and 12 m above the plain surface, has been known since a long time.

These elongate with a NW-SE (Dinaric) trend and represent the surface response to the Quaternary activity of buried lines (CAVALLIN & MARCHETTI, 1995; FONTANA, 1999).

It is only using a DEM-derived map analysis (3D and shaded relief maps), compared with a microrelief map, that the morphology of the Pozzuolo (P) ridge can be fully perceived (Fig. 24a).

The same applies to the inner and northern ridges (the Bonavilla ridge), where digital maps clearly show the latter to be more continuous and regular than the former.

In addition, the Bonavilla ridge sharply cuts off and uplifts deposits of different age (Figs. 1 and 7), i.e. widespread pre-LGM glaciofluvial gravels and fan-shaped gravels and sands related to the late glacial (and ?post-LGM) Cormor Torrent dynamics.

Consequently, the uplifting was active later than the onset of the glaciofluvial deposits (pre-LGM, Late Pleistocene) and coeval with the first entrenchment of theTorrent Cormor (late glacial - early Holocene).

Shaded relief (Fig. 24a) and microrelief map analyses (Fig. 11), together with the field survey, clearly show that the outer ridge uplifting south of Udine developed before the inner ridge. Moreover, the DEM-derived map analysis (Fig. 24a) supports an interesting working hypothesis.

This is based both on the morphological trends of the Pozzuolo and Bonavilla ridges and on the different shortening rates (Figs. 23a, b) shown by geophysical profiles of the Friuli upper plain (FANTONI *et alii*, 2002).

The shortening rate is lower in the sector located west of Udine, in which a gentle deep anticline deformation stopped in Early Pleistocene times and was buried under several tens of metres of undisturbed fluvial and glaciofluvial Quaternary sediments (Fig. 23b). Conversely, south of Udine the shortening is decidedly higher and is due to a thrust system whose last activity is Late Pleistocene-Holocene in age (Fig. 23a).

The evidences supported by the digital map analysis, compared with the subsurface data (FANTONI *et alii*, 2002), show that the ground deformations are probably constrained between two systems of conjugate faults, as shown in Fig. 24b.

This interpretation is also consistent with the non-contemporaneous uplifting of the outer and inner ridges. Besides, the fault system pattern is

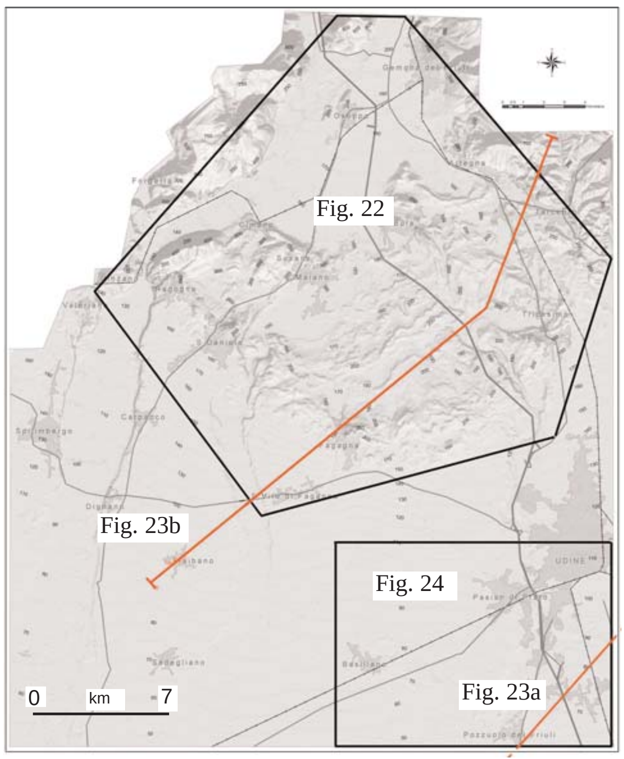


Fig. 21 - *The sketch map shows the location of Figs. 22 and 24, devoted to highlighting morphological features related to active tectonics, and the traces of the seismic profiles crossing the area (see Figs. 23a, b).*

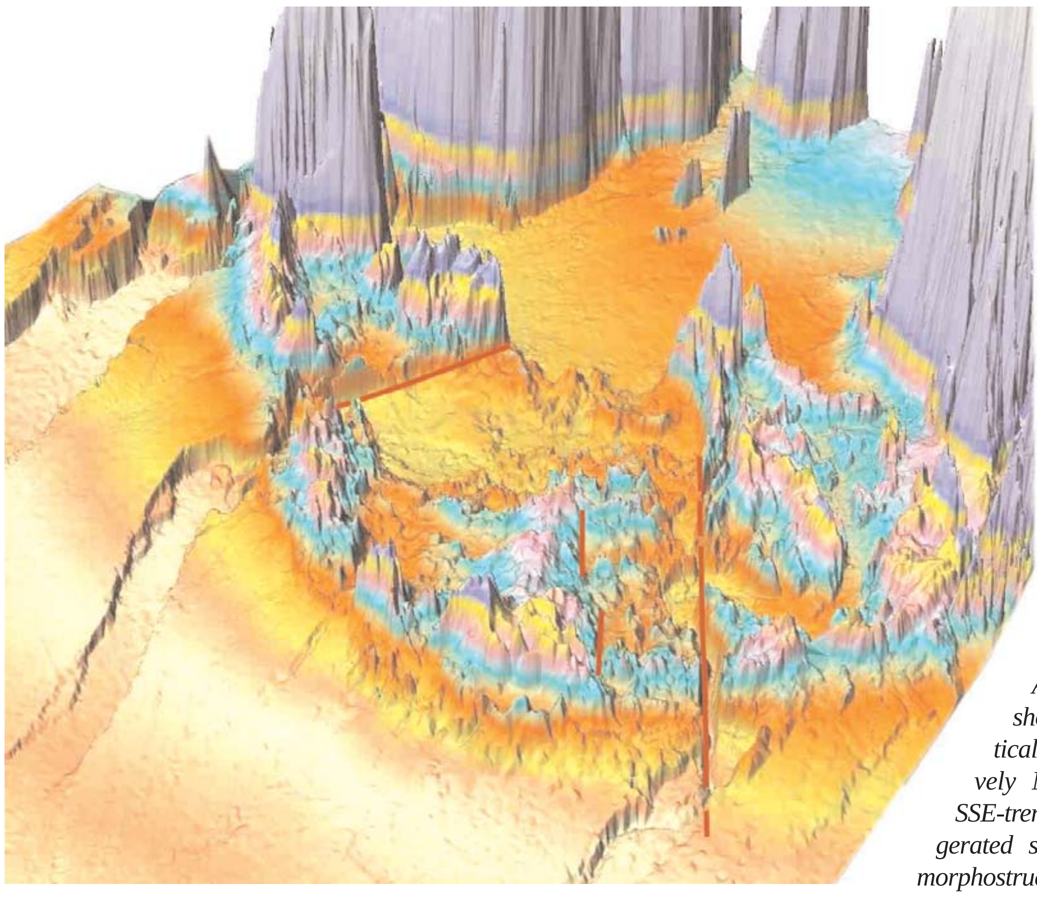


Fig. 22 - *The Tagliamento Moraine Amphitheatre area shows evidence of two vertical fault systems, respectively NNE-SSW- and NNW-SSE-trending. The vertical exaggerated scale greatly highlights morphostructural trends.*

consistent with a N10°-15°E-trending maximum stress; the same value has been obtained for the same area (Bressan *et alii*, 2003) by means of focal mechanism inversion analysis.

CONCLUSIONS

The area studied is located in the eastern Southern Alps, at the transition between the Carnic and Julian Alps and the central Friuli upper plain.

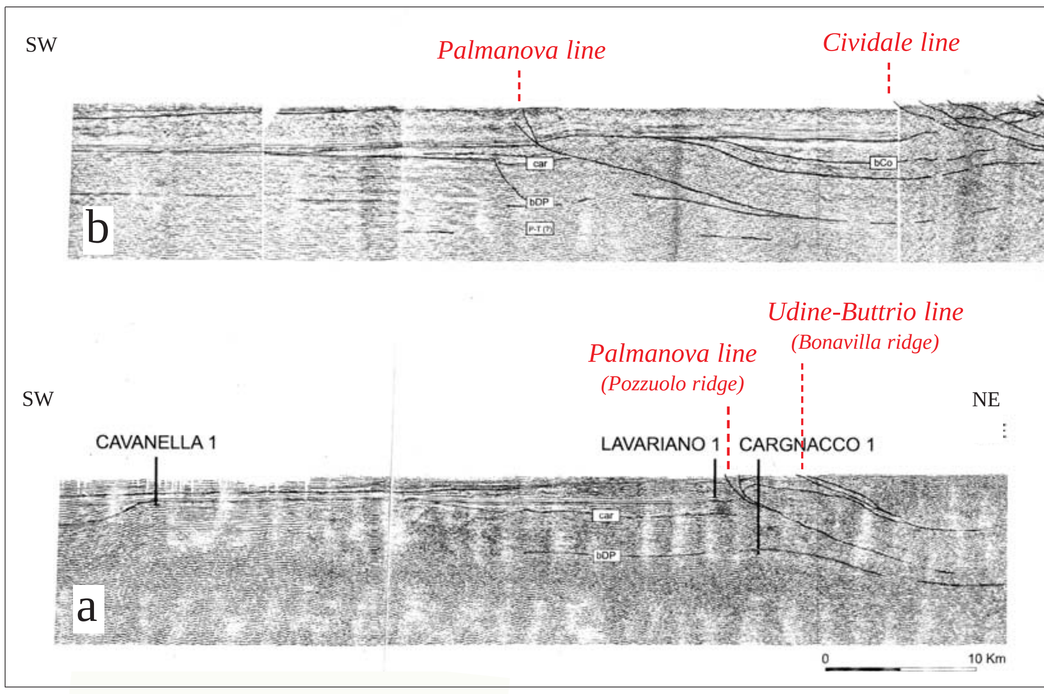
As a case study it provides evidence of the essential support provided by the analysis of DEM-derived maps (microrelief, shaded relief, 3D) to the field survey approach, enabling to achieve a more accurate final interpretation of landform evolution.

DEMs are especially useful for low-gradient surfaces and/or highly urbanized areas, where field surveys are difficult to carry out or even pointless. In particular, the case study highlights the essential contributions of relevant DEM-derived maps in the case of: a) low gradient topography; b) active tectonics affecting Quaternary deposits; c) palaeo-environmental domains to be singled out; d) morphological inheritances affecting the surface.

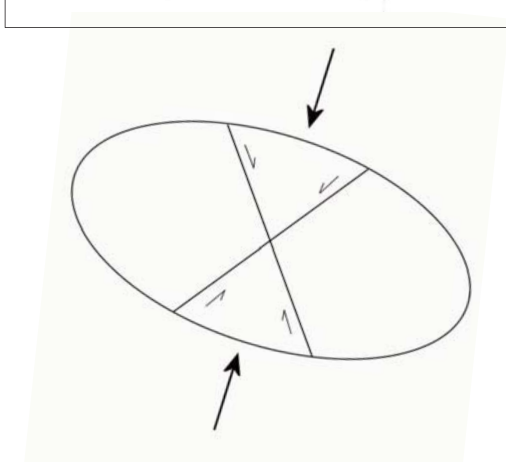
Moreover, DEM-derived maps allow meaningful sites in which to carry out targeted surveys a priori to be located.

The complex evolutionary framework of the study area arises from an alternation and interaction of climate fluctuations, erosional and depositional processes, active tectonics and the inherited morphology on which all these factors acted.

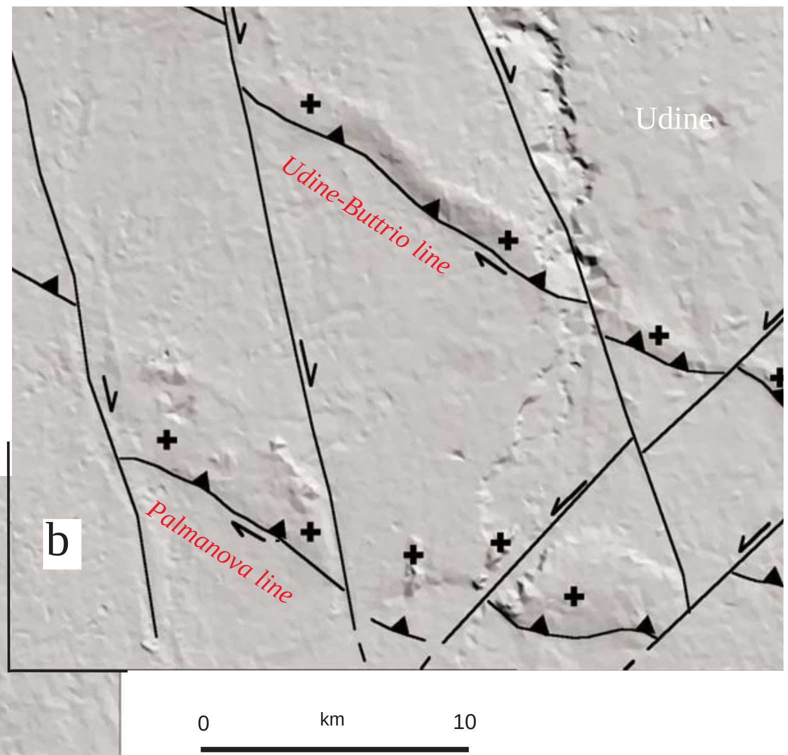
The case study perfectly illustrates the essential improvement brought by DEM analysis to the interpretation of field data (e.g. the pre-LGM ice snout extent). Otherwise, if used alone without the support of a classic geological survey (e.g. in the case of the reconstruction of a former fluvial network) or without geophysical investigations (e.g. to detect active tectonics and deformation style) it can be misleading.

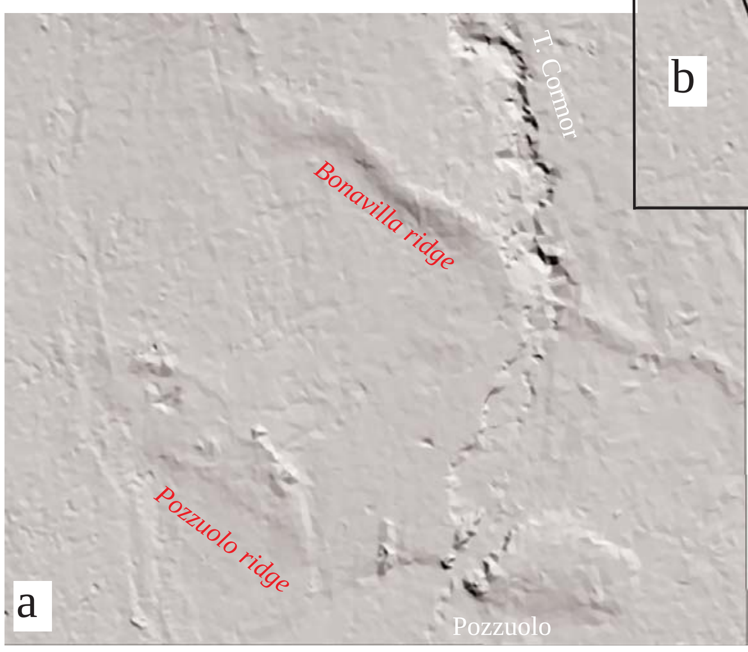


Figs. 23a, b - *The seismic profiles show the different deformation rate existing in adjoining areas of the Friuli upper plain sector (modified according to* Fantoni et alii, *2002).*



Inferred maximum stress orientation (N13°E)





Figs. 24a, b - *The vertical exaggerated scale of the shaded maps lend themselves to highlight the morphology of the upper plain south of Udine. By comparing surface (Fig. 24a) and subsurface data (Figs. 23a, b), the interpretation shown in Fig. 24b can be proposed. The gentle morphostructural highs related to the Quaternary activity of the Udine-Buttrio and Palmanova lines show a peculiar distribution which seems to be consistent with a conjugate fault system.*

ACKNOWLEDGEMENTS

The authors thank M. Ghidini (Regione Friuli-Venezia Giulia) for enabling the use of the digital technical map (CTRN) database of the Regione Friuli-Venezia Giulia (agreement between F-VG Region-Bologna University), from which it was possible to draw all the DEM-derived maps. Warm thanks also to P. Ferraresi, M. Roma and M. Zia for their kind assistance.

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