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EXPLANATORY NOTES OF THE GEOMORPHOLOGICAL MAP OF THE ALTA BADIA VALLEY (DOLOMITES, ITALY)

ABSTRACT: PANIZZA M., CORSINI A., GHINOI A., MARCHETTI M., PASUTO A. & SOLDATI M., *Explanatory notes of the Geomorphological map of the Alta Badia valley (Dolomites, Italy).* (IT ISSN 0391-9838, 2011).

This paper shows the geomorphological aspects of the Alta Badia valley (Autonomous Province of Bolzano, northern Italy), located in one of the best known areas of the Italian Dolomites, between the passes of Gardena, Campolongo and Valparola-Falzarego. The paper is also aiming at illustrating the annexed Geomorphological map of the Alta Badia valley (Dolomites, Italy), at 1:20,000 scale.

The present morphological features of the Alta Badia valley is the result of a complex interaction between geological structure and modelling processes that have mainly been active since the Last Glacial Maximum (LGM). Stratigraphy and structure controlled the formation of subhorizontal dolomitic plateaus, flanked by sub-vertical slopes that are linked to less inclined ones - where softer materials mainly outcrop - by broad scree slopes and talus cones.

Landforms in the area are largely related to mass movements that have progressively remodelled the main valleys during the Holocene, partly masking the older traces of glacial origin. Landslides - that took place after the progressive glacier retreat - showed an intense period of activity at the end of the Lateglacial, followed by alternated clustering during the Holocene, as witnessed by several radiometric datings. Slope processes have gradually become the main geomorphological feature in the valley. The slopes are, at present, characterized by the presence of extensive scree slopes and talus cones, debris flow accumulations and different types of landslides. Sometimes, landslide bodies dammed the valley bottoms forming lakes. This is the case of the plain of Corvara in Badia that is made up of alluvial and lacustrine deposits accumulated as a consequence of the repeated damming of the valley since the early Holocene.

The traces of the LGM consist of scattered and small moraine deposits on plateaus as well as of broader outcrops along the slopes, where they have largely been mobilized by subsequent mass movements. On the other hand, glacial landforms shaped during the Lateglacial are mainly located in the lowest part of slopes and, occasionally, along the valley floors, especially in the centre-eastern part of the study area.

Recently, the intense urbanization and the development of the ski tourism, on which the economy of the valley is based, have been modifying the landscape with ever growing intensity.

KEY WORDS: Geomorphological map, Alta Badia valley, Dolomites, Italy.

INTRODUCTION

The Alta Badia valley is part of the Italian Dolomites, which are universally known for their scenic beauty and scientific interest. The long and complex geological and geomorphological history of this region has shaped typical and spectacular landforms characterised by huge dolomite vertical cliffs rising from gentle slopes made up of darker terrains, where woods, pastures and scattered hamlets are located, as well as important tourist infrastructures.

The Research Group of Geomorphology of the University of Modena and Reggio Emilia has coordinated and participated in several national and international projects concerning the study of the geomorphological aspects of the Dolomites, also in collaboration with the National Research Council of Padua. The research carried out for more than 20 years have mainly regarded methods and techniques of geomorphological mapping, slope movement analysis and landslide hazard assessment. These investigations have been funded by different Framework Programmes of the European Commission (e.g., «Environment» and «Environment and Climate» programmes) and by national programmes (e.g., Miur-Cofin / Prin and Carg projects). The Geomorphological map of the Alta Badia synthesises the results from the above mentioned investigations.

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The research has been carried out within a series of national and EC-funded projects, among which the last one in time is the ENSURE Project ("Enhancing resilience of communities and territories facing natural and na-tech hazards" - EC Contract n° 212045). The Authors are grateful to the colleagues of the Ufficio Geologia e prove materiali of the Autonomous Province of Bolzano for the scientific and technical support during the survey and mapping, as well as to the officers of the Comune di Corvara in Badia and the Consorzio Turistico Alta Badia for the precious and continuous support.

This text is derived from a lecture given at the 3rd Meeting of the Italian Association of Physical Geography and Geomorphology, held in Modena on September 13, 2009 in honour of Prof. Mario Panizza.

The mapped area is part of the Dolomites which were included in June 2009 in the Unesco World Heritage List. The Dolomites entered the Heritage List because of their exceptional beauty and unique landscape (criterion VII), together with their scientific importance for the geological and geomorphological viewpoint (criterion VIII). In particular, with reference to criterion VIII and Geomorphology, it was stated that «*The Dolomites are of international significance for geomorphology, as the classic site for the development of mountains in dolomite limestones. The area presents a wide range of landforms related to erosion, tectonism and glaciation. The quantity and concentration of extremely varied carbonate formations is extraordinary in a global context, including peaks, towers pinnacles and some of the highest vertical rock walls in the world… (omission)… Taken together, the combination of geomorphological and geological values creates a property of global significance*».

An original geomorphological key criterion, presented for the Unesco application, is the geomorphodiversity (Panizza, 2009a) of the Dolomites, which is related both to their differences with other mountain areas (extrinsic) and to their variety (intrinsic). At global scale, the extrinsic value is given by their monumentality, originality and spectacularity, that characterise and distinguish them from all other World's mountains. Moreover, within the Alpine chain (and not only) they offer a very wide, complex and emblematic range of landforms: mainly structural forms related to ancient or recent earth crust movements, or forms related to the various rock types that crop out. Referring to the intrinsic variety, the above mentioned landforms cross with others that, due to their heterogeneity and complexity, form, within the Dolomites, an almost complete scientific and teaching spectrum. Actually, it can be stated that the Dolo-mites represent a high-mountain open-air laboratory of a geomorphological heritage that has an exceptional World's value.

Landforms linked to current climatic conditions and to climatic conditions that recurred through the last geological periods can be widely recognised, such as glacial, periglacial and gravitational features.

With specific reference to the Alta Badia valley, the areas that were included in the World Heritage List of Unesco are those where the human pressure is lesser, that is the mountain groups of Gherdenacia, Conturines, Lagazuoi and Setsas.

GEOGRAPHICAL AND CLIMATIC SETTING

The Alta Badia valley lies in the southern sector of the Eastern Alps, mainly within the Autonomous Province of Bolzano and only for a small portion within the Province of Belluno (Veneto Region) (fig. 1). The area included in the geomorphological map is about 128 km^2. The valley can be accessed from the west through the Gardena Pass (2121 m a.s.l.), from south-west through the Campolongo Pass (1679 m), from the north, through the narrow La Gran Ega valley and from south-east, through the Valparola Pass. The main mountain peaks are Gherdenacia (3025 m) to the north-west, Piz Boè (3151 m) to the southwest, Piz dles Conturines (3064 m), Piz Lavarela (3055 m) and the Lagazuoi Mountain (2752 m) to the east, Setsas (2138 m) and finally Pralongià (2571 m) to the south and Piz la Ila (2078 m) and Col Alt (1980 m) in the centre.

Concerning hydrography, the study area is part of the Adige River basin. The water courses with permanent regime are Rü de Pisciadù - starting from the northern base of

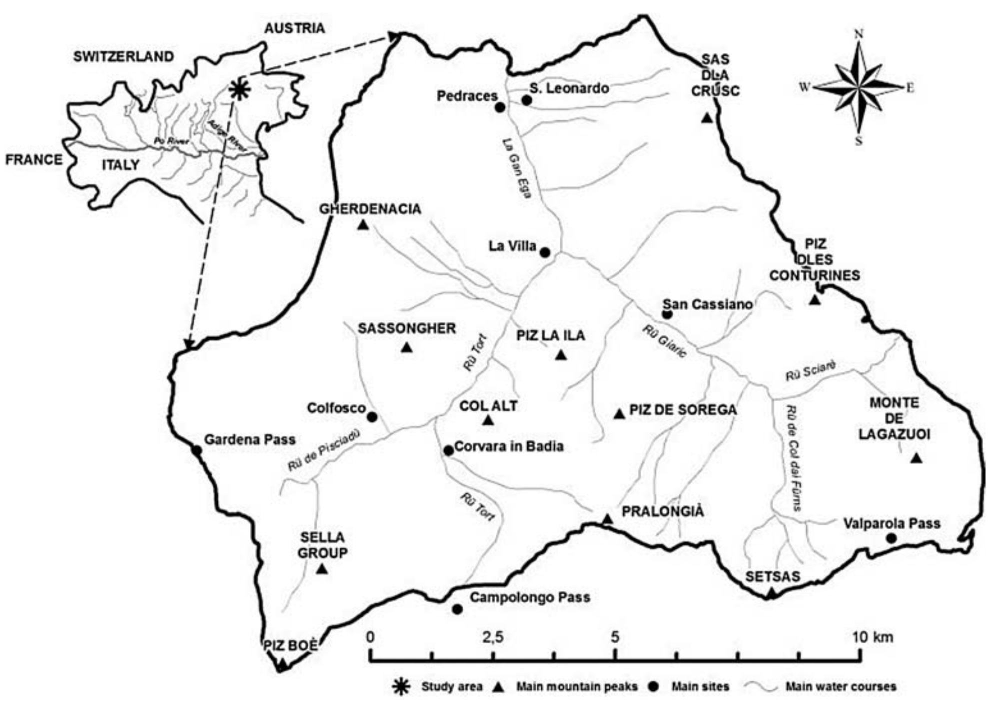


FIG. 1 - Geographic sketch map of the Alta Badia valley (Dolomites).

the Sella Group - and Rü Tort - originating near the Campolongo Pass, flowing through Corvara in Badia and then heading towards north-east. At La Villa, the Rü Tort joins the Rü Giaric that drains the valleys of San Cassiano and Valparola, giving origin to La Gran Ega. Water courses are mainly fed by meteoric waters seeping through the fractures of the dolomitic massifs, whose contact with the underlying marly and clayey formations give rise to numerous springs lying at a mean altitude of about 2000 m. Important water input comes also from talus cones, from the hypodermic flux of forest and high-pasture soils and, during the most intense precipitation events, from debris flow channels.

The main villages of the Alta Badia valley are Colfosco (1640 m), Corvara in Badia (1560 m), La Villa (1420 m), San Cassiano (1540 m) and Badia (1375 m). Although of limited extent, they have acquired through time high tourist standards, for both winter and summer holidays. For this reason human-induced landforms are evident on all slopes, mainly related to the development of skiing facilities with a dense network of cable-cars and chair-lifts reaching altitudes above 2500 m (see the specific frame in the geomorphological map, showing the distribution of ski slopes).

Buildings, infrastructures and the main industrial and commercial activities are located in the valley bottoms, while meadows and forests occupy the remaining areas at the foot of the dolomite cliffs.

The climate of the area can be deduced by the analysis of meteorological series from the stations of Corvara in Badia (1540 m) and of La Villa (1390 m), collected by the Mountain Basin Service of the Autonomous Province of Bolzano (fig. 2). The mean annual precipitation recorded during the period 1990-2008 is 950 mm. The rainiest months are the summer ones, from June to August, while the driest ones are the winter ones, the latter having mostly snow events.

The mean annual temperature of the period 1990-2008 is 4.8°C. The coldest month is usually January (mean –4.9°C), the warmest is July (mean 15°C). These temperature and

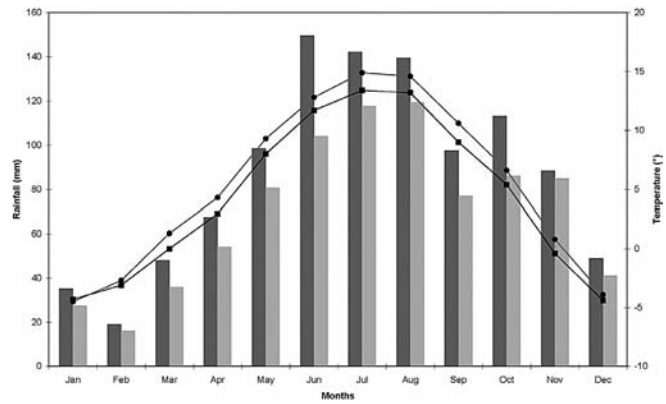


FIG. 2 - Mean monthly values of rainfall (columns) and temperature (dotted lines) at the meteorological stations of Corvara in Badia (1540 m) and of La Villa (1560 m) in the period 1990-2008. Dark-grey blocks and line with squares refer to the Corvara in Badia station; light-grey blocks and line with circles refer to the La Villa station.

precipitation values place the climate of the area within the Köppen's (Köppen, 1931) class «Dfc», i.e., «Temperate-cold or Boreal». From 1960 to 1990, the mean annual temperature was 3.9°C, that of January was –6.2°C and that of July was 14.2°C. Therefore the most recent mean annual temperature appears about 1°C higher. In particular, the mean temperature of the coldest month is 1.3°C higher and the mean temperature of the warmest month is 0.8° higher.

Examining the precipitation events with heights above 50 mm lasting for 1 to 5 consecutive days, during the period 1990-2008, it can be noticed that October and November, and secondarily June, July and August, recorded the highest number of events. In comparison with the period 1972-1990, during the last 18 years the frequency of those events has doubled, with the exception of 24-hour lasting events that have had a smaller increase. According to Van Steijn & *alii* (1997) and to Dikau & *alii* (1996), those high-precipitation events are the main cause of debris flow initiation in the alpine area, in particular on scree or talus cones at the foothills of massifs. Investigations in the Dolomites by Marchi & Tecca, already in 1996, showed how the autumn months and the summer ones record the highest number of debris flow events. The precipitation data from the last two decades confirms that picture.

It is interesting to notice that from the period 1960-1990 to the last two decades (1990-2010), the frequency peak of intense precipitation events has shifted from July to October.

The snow precipitation data from the Hydrographical Office of Bolzano and Trento, recorded almost continuously from the winter season 1981-82 to the 2005-06 one, highlight a mean daily snow thickness for the valley of some 80 cm. The mean daily snow thickness varies from 0.9 cm to 4.3 cm, with extreme values of 140 cm and 105 cm respectively in February 1986 and in February 1991.

PREVIOUS STUDIES

The geological features of the Dolomites, including those of the Alta Badia valley, have been studied since the 18th century. For a complete summary of old geological studies, it can be referred to the monographs by Leonardi (1967), Bosellini (1996) and Bosellini & *alii* (1996).

Anyhow, it is worth mentioning that the first geological research in the study area dates back to Münster & Wissmann (1841) who described in details the fossil fauna of the S. Cassiano Formation. The first geological mapping of the Badia valley was done by Fuchs (1844), while working at his geological map of the Venetian Alps. Penck & Brückner (1909) visited the valley during their research on glaciers of the Alps. More detailed geological studies were done by Ogilvie Gordon (1927, 1928, 1934) and by Mutschlechner (1933); the latter was the first one to describe, in a complete way, the Raibl Formation, close to Valparola Pass. Von Klebelsberg (1936) hypothesized the presence in the Badia valley of a glacier coming from the Pusteria Valley during the Last Glacial Maximum. B. Castiglioni (1930; 1936) and G.B. Castiglioni (1964) described the extent of stadial glacial deposits within a wider research covering the whole Dolomites. Leonardi (1967) analysed the main tectonic features of the area, among those of the entire Dolomites. More detailed papers are those by Bosellini (1965; 1982). Sommavilla & Rossi described the petrographic and sedimentological characteristics of the geological formations (in Brondi & *alii*, 1977), within a research programme related to the elaboration of the geological sheet no. 028 «La Marmolada» (1:50,000 scale) of the Geological Map of Italy.

The most recent studies of the Triassic stratigraphy are those by De Zanche (1990), De Zanche & *alii* (1993), De Zanche & Gianolla (1995), Gianolla (1995), Loriga Broglio & Neri (1995) and Keim & *alii* (2001).

As for geomorphological aspects, Panizza carried out the first detailed surveys in the area and surroundings, analysing ad mapping Quaternary landforms (in Brondi & *alii*, 1977).

After that, many geomorphological studies have been undertaken in the same areas. Besides those describing the geomorphological evolution of the Dolomites (Panizza & *alii*, 1978; Carton & *alii*, 1980; Corsini, 1995, 2000; Ghinoi, 1999; Corsini & Panizza, 2003; Coratza & *alii*, 2005), other studies have been done to deepen applied issues (Corsini & *alii*, 1997; 1999; 2005; Ghinoi, 2003; Ghinoi & Chung, 2005; Fazzini & Panizza, 2006) and to favour landscape exploitation (Panizza, 1988; Carton & Panizza, 1991; Carton & Soldati, 1993; Coratza & *alii*, 2004; Bruschi & *alii*, 2009; Gianolla & Panizza, 2009; Gianolla & *alii*, 2009; Panizza, 2009a; Panizza, 2010; Soldati, 2010).

Specific research on geomorphological hazards in the Alta Badia valley have been carried out in collaboration with the Municipality of Corvara in Badia and with the Autonomous Province of Bolzano, that led to the elaboration of the Risk Plan of the Municipality of Corvara in Badia and of the Geological Hazard Map of the Sheet No. 28 «La Marmolada» (CARG Project) (Corsini & Panizza, 2007).

The geomorphological investigations carried out in the Alta Badia valley enabled also the collection of several dating of landslides since the Late-glacial in the area. A series of studies, also part of national research projects (e.g., PRIN 2002 - Co-ordinator M. Soldati), pinpoint significant correlations between climate changes and landslides and, more generally, to paleo-environmental reconstructions (Corsini & *alii*, 2000; 2001; Borgatti & *alii*, 2004; 2006; Soldati & *alii*, 2004; 2006; Soldati & Borgatti, 2009; Borgatti & Soldati, 2010).

GEOLOGICAL ASPECTS

Stratigraphy and outcropping formations

The Alta Badia valley is included in the Geological Sheet No. 11 «Monte Marmolada» (1:100,000 scale) of the Servizio Geologico d'Italia (1970), in the Sheet Nr. 28 «La Marmolada» (1:50,000 scale) of the Geological Map of Italy (Servizio Geologico d'Italia, 1977) and in the most recent «Geologische Karte der Westlichen Dolomiten - Carta Geologica delle Dolomiti Occidentali» of the Autonomous Province of Bolzano (Brandner & *alii*, 2007). The latter reports the new terminology which has been recently given to the geological formations outcropping in the study area. This comes from a process of re-interpretation of sedimentological and stratigraphic aspects that lead to a modification of the traditional stratigraphic schemes by Bosellini (1996).

The stratigraphic sequence that formed from the Upper Permian to the Lower Cretaceous, outcrops discontinuously in the study area, often being doubled by thrusts and bended forming anticlines. The crystalline basal formations lie just outside the study area, but some lithologies can be found as sparse clasts within glacial sediments from the LGM.

The rocks outcropping in Alta Badia valley have been classified in the geomorphological map using a criterion based on lithological subdivisions. More properly, not only the lithological composition has been taken into account, but also the response of each lithotype to exogenous agents. A chronostratigraphic criterion has been also added to avoid grouping lithologically similar formations, but chronologically far from each other (see the stratigraphic sketch of the Permian-Upper Triassic sequences on the attached geomorphological map). As for the terminology of the geological formations, reference is made to the recent «Geologische Karte der Westlichen Dolomiten - Carta Geologica delle Dolomiti Occidentali» (Brandner & *alii*, 2007).

In synthesis, the mountain groups of Gherdenacia, Sella, Setsas, Conturines and Lagazuoi are mainly formed by massive or stratified dolomites from the Medium-Upper Triassic (Dolomia Cassiana and Dolomia Principale formations), with brittle mechanical behaviour and, secondarily, by marls and silts from the Ladinian and Carnian (Pordoi, Heiligkreutz and Travenanzes formations), with ductile behaviour (figs. 3 and 4).

The Pralongià plateau and the slopes at the base of the dolomitic cliffs of the Sella Group, of the Gherdenacia, of the Sas dla Crusc and of the Piz de Lavarela are formed by complex lithologies, composed by pyroclastic sandstones and siltstones from the Medium Triassic (Wengen Formation) and by sequences of calcarenites, marls and silts form the Medium-Upper Triassic (S. Cassiano Formation). The mountain ridge Piz la Ila - Col Alt, its north-west fac-

FIG. 3 - The Sella Group in the background and the Pralongià plateau in the foreground.

FIG. 4 - The Gherdenacia Group in the background and the Pralongià plateau in the foreground.

ing slope and the southern foothills of the Gherdenacia (from Verda to Fontana di Salvan) are formed: sandstones, tuffs, lavas and megabreccias in volcanic matrix from the Medium Triassic (Fernazza Group and Caotico Eterogeneo), and limestones, dolomites, sandstones, breccias and marls from the Upper Permian - Lower Triassic, affected by a dense network of fractures (Bellerophon, Werfen, Contrin, Moena, Buchenstein and Zoppè formations).

LITHOTECHNICAL GROUPS

(Numbering from 7 to 1 in the following headings referts to the lithotechnical groups depicted in the annexed Geomorphological map)

Calcareous marls, marls and sandstones of Permo-Triassic age (7a-7d)

The base of the stratigraphic sequence is given by lithologies that were formed, initially, under shallow tropical waters often subject to strong evaporation and to the mechanic action of waves. In particular, the *Bellerophon Formation* (Upper Permian) is composed by cyclic alternations of marly greywackes with clays, gypsum nodules, frequent intercalations of marly-bituminous dolomi-te strata and, in the upper portion, fossil-rich grey limestones with black coloured, marly-clayey interbedding («facies badiota»), testifying transgression events. It crops out in limited areas at the base of the Morbiac Formation, west of Colfosco, and on the Col Maladët, north of Pescosta.

The *Werfen Formation* (Upper Permian - Lower Triassic) is a heterogeneous sequence of calcareous strata, marls, sandstones, silts and argillites, rich of fossils, that formed after repeated transgressions and regressions. It crops out in limited areas, west of Piz la Ila, where the Campil Member (sandstones, silts and siltstones), the Val Badia Member (micritic limestones and marls), the Siusi Member and the Gastropods Oolite (calcareous tempestites, marls, marly and oolitic limestones) are present. It also crops out on Col Maladët, north of Pescosta, with the Mazzin Member together with the Tesero Oolite (limestones, marls and calcarenites).

The important Upper-Anisian marine transgressive phase led to the deposition of bituminou-smicritic limestones, in alternation with marls and fine terrigenous clasts which compose the *Morbiac Formation* (Upper Anisian). The deposition environment was a shallow sea within the Contrin's calcareous platform. It crops out along a limited narrow stripe on the slope north-west of Colfosco, showing a basal contact with the Bellerophon Formation.

Coarse and fine-grained breccias, sedimented in platform and basin environments, compose the *Moena Formation* (Upper Anisian), whose outcrop is limited to a small area north of Col Alt.

Afterwards, deeper sea floors hosted the deposition of the sediments composing the *Buchenstein Formation* (Upper Anisian - Lower Ladinian), previously identified as the «Livinallongo Formation». The sediments are bituminous limestones, nodular limestones interbedded by marly layers and levels of green tuffs and ashes (testifying a nearby explosive volcanism), deposited in basins between the Ladinian coral platforms. It crops out on the slope between Col Alt and Piz la Ila and north of Colfosco, in contact with the Contrin Formation. It also crops out north of Piz la Ila, at Col Frata and at Col Pici Runc.

The deep-sea turbidites of the *Zoppè Formation* (Upper Anisian - Ladinian) close the Permo- Triassic lithological sequence. They are composed by arkosic sands that during the Lower Ladinian derived from the erosion of metamorphic and granite rocks of the Venetian plain, which underwent extensive tectonic uplift. The Zoppè Formation crops out near Piz la Ila, between Col Fata and Col Pici Runc.

Lavas, pillow lavas, tuffs, sandstones and megabreccias with volcano-clastic matrix (6, 6a)

During the Upper Ladinian, an intense submarine volcanism led to the deposition of effusive products such as pillow lavas and intrusive bodies such as dikes and sills.

Previous to that phase was the sedimentation (due to deep sea mega-slumps) of debris produced after earthquakes and volcanic activity. The deposits are composed by megabreccias in volcanic and volcano-clastic matrix and form the «*Caotico Eterogeneo*» (Upper Ladinian). It crops out near Col Frata and Col Pici Runc, north of Piz la Ila, and along a narrow SW-NE stripe that stretches from Piz Dalander to Pre da Sala, passing through Col Alt, Pre Ciastel and Piz la Ila. Scattered outcrops can be found at Vorda, north of Col Maladët, along Val de Merscia, west of Pescosta, and along a WSW-ENE stripe that stretches from Colfosco to Pra de Tru. In this area the «Caotico Eterogeneo» is in contact with the Buchenstein and Contrin formations.

The pillow lavas, tuffs and sandstones of the *Fernazza Group* (Upper Ladinian) derive from the sedimentation of products from the explosive pulverization of lavas in sea water. The most extensive outcrop of the area is along the SW-NE stripe that links Corvara in Badia to the San Cassiano valley, passing through Col Alt, Piz la Ila and Peres da Fuchs.

The pillow lavas and the blocky lavas of the Fernazza Group (Upper Ladinian) crop out exclusively on the left flank of Rü de Pisciadù and north of Colfosco, at Pra de Tru and below Utia Edelweiss.

Post-volcanic basinal sediments (5a, 5b)

During the Upper Ladinian, the debris produced by the erosion of the old volcanoes of Predazzo and Monzoni were deposited on the deep-sea floors between the Ladinian coral reefs. A thick volcano-clastic sequence formed, making up the *Wengen Formation* (Upper Ladinian), characterized by significant lateral and vertical facies variations that cause an extreme variability of its mechanical behaviour: the silty-arenaceous, compact levels are mechanically brittle, while the claystone strata show a ductile behaviour. More specifically, the formation is composed by volcano-clastic sandstones, clays and, secondarily, by marls. Moreover, it has frequent alternations of strata composed by platform debris, breccias and «Cipit blocks», i.e., calcareous blocks detached by coral reef scarps and slid into the basin. In the study area it occupies the basal and medium portion of the majority of valley flanks. The Wengen Formation crops out in the area of Corvara in Badia, at the foothills of the Sella Group, of the Pralongià and of the Col Alt. It is also observable in the San Cassiano valley, in particular, west of Piz de Surega and at its base, and between the villages of La Villa and San Leonardo, at the base of Sas dla Crusc and of Col da Oi. In those outcrops, the heteropical upper contact with the S. Cassiano Formation is clearly visible. In the Colfosco valley, the formation crops out on the medium portion of the left flank, showing its basal contact with the Ladinian volcanic/volcano-clastic sequence, and at the Gardena Pass.

The progressive shift towards more carbonate-rich sediments derived from the erosion of coral platforms determined, during the Carnian, the deposition of the *S. Cassiano Formation* (Upper Ladinian - Lower Carnian). It is a thick sequence of marls, marly limestones, calcareous marls, calcarenites and breccias with a flysch-like bedding. It commonly overlies the Wengen Formation with which it has an initial partial heteropy. It is totally heteropical with the Dolomia Cassiana Formation. Large calcareous blocks can also be found (Calcari del Cipit). Outcrops are visible on the upper part of the Pralongià and of Piz de Surega, on the eastern flank of Crep de Munt (Sella Group) and on the northern slope of the Col da Oi. Sparse and limited outcrops can be found north of Cima Les Pizades, at the Valparola Pass, on the right flank of the San Cassiano valley, on the western and eastern sides of Val Badia, between San Leonardo and La Villa, and at the foothills of the dolomitic massifs of the Sella Group and of the Gherdenacia, in the Colfosco valley.

Terrigenous-evaporitic sequences (continental and neritic) (4)

Terrigenous-evaporitic sequences locally outcrop in the studied area. They are made up of alternations of red and green marls, argilloscists, oolitic limestones, varicoloured marls, sandstones with interbedded red clay shales, black shales, carbonatic marls and marly dolomites of the Pordoi, Heiligkreuz (Fedares, Di Bona, Falzarego and Lagazuoi members) and Travenanzes formations.

The *Pordoi Formation* (Lower Carnian - Upper Carnian) is an alternation of dolomites, marly dolomites, stromatolitic dolomites, marls and greenish clayey levels. The lower boundary is sharp on the topset and/or on the inclined strata of Dolomia Cassiana, while the upper boundary is with Dolomia Principale. It crops out all along the Val Badia side of the Gherdenacia, within a wide stripe starting from the Col Toron and from the Lech de Crespeina (west) to the Ciampani peak (to the north-western limit of the study area), showing a sub-horizontal attitude. Other outcrops can be found on the Sella Group, discontinuously from Crep de Munt to the Tor di Ciamurc (E-W trend), and between Le Valun and Pan de Sass, close to the south. Megabreccias are visible only in a limited outcrop on the northern slope of the Sella Group, in the Valun de Pisciadù, north of Lech de Pisciadù.

The *Heiligkreutz Formation* (Lower Carnian - Upper Carnian) is a carbonatic-siliceous-clastic unit, formed in the residual basin of the S. Cassiano Formation. It is made of four members: Fedares, Di Bona, Falzarego and Lagazuoi. The Fedares Member (Upper Julian) is composed by black shales, marls, calcareous marls and limestones. It crops out only in small areas on the right flank of Val Badia, south-east of I Pici Crëps (under the Sas dla Crusc) and in the near site of La Crusc. The Di Bona Member (Upper Julian - Lower Tuvalian) is composed by oolitic limestones, loferites, varicoloured marls, micritici and silty limestones, laminated dolomites, conglomerates, sandstones and argilloscists. It crops out along narrow stripes, parallel to the contour lines, at the base of the Piz dles Conturines, at Banch de Bisces and west of Piza dl Lech, north of Monte de Lagazuoi. The Falzarego Member (Lower Tuvalian) is composed by fine grained sandstones with argilloscists interbedded and conglomerates, with a ripple-like (crossed or hummocky) stratification. It crops out only in Valparola, in different scattered areas between the Valparola Pass and the peak Les Pizades, in stratigraphic and tectonic contact with the Dolomia Cassiana. More specifically, at Prà de Ciàmena it shows a clear crossed stratification. The Lagazuoi Member (Lower Tuvalian) (Dürrenstein Dolomite Auct.), is formed by dolomitized oolites, with a crossed stratification, in alternation with arenaceous strata, and by thick strata of vacuolar dolomite. It crops out along narrow stripes parallel to the contour lines at the base of the Piz dles Conturines, at Banch de Bisces, and west of Piza dl Lech, north of Monte de Lagazuoi, with the basal stratigraphic contact with the Di Bona Member and the upper stratigraphic contact with the Travenenzes Formation. Less significant outcrops can be found under Sas dla Crusc, at Pici Crëps and at La Crusc.

The *Travenenzes Formation* (Upper Carnian) (Raibl Formation Auct.), is composed by alternations of red and green marls, argilloscists with dolomite and stromatolites. Its lower boundary is sharp on the Heiligkreuz Formation (Lagazuoi member); the upper boundary is gradual with the Dolomia Principale. It extensively crops out in Valparola, at Prà de Ciàmena, Ciampei and west of Vallone Pudres. Sparse outcrops can be found around the Valparola Pass, while under the Piz dles Conturines (Banch de Bisces), west of Piza dl Lech and north of Monte de Lagazuoi it represents the upper boundary of the Dolomia Cassiana - Heiligkreuz formation sequence.

Post-volcanic dolomites of Ladinian and Carnian age (3a-3c)

The dolomitic formations building up the main mountain massifs have been subdivided into three groups: the well-stratified dolomites of the Contrin Formation, the dolomites and the platform limestones belonging to the «Sciliar Group» (Sella Subgroup, Dolomia Cassiana and Denti di Terra Rossa formations) and the cyclic sequence of metre thick light grey dolomites of the Dolomia Principale formation.

The *Contrin Formation* (Upper Anisian) is composed by grey to light greenish yellow, massive or well-stratified dolomites. It formed within the warm and clear waters of a shallow tropical sea (Bosellini, 1996). In the Badia valley the formation crops out along the slope that links Col Alt to Piz la Ila, in alternation with the Werfen and Buchenstein formations. It crops out also at Col Maladët, north of Pescosta, near Colfosco and at Pra de Tru, east of Gardena Pass.

The *Sella Subgroup* (Upper Ladinian - Lower Carnian) is composed by post-volcanic platform limestones and by thick strata of well-stratified dolomites (lagoon facies, topset), showing typical inclined strata. Where it is heteropical with the Wengen and S. Cassiano formations, the subgroup is divided into two units: the Denti di Terra Rossa and Dolomia Cassiana formations. It forms the basal portion of the Sella Group and of the Gherdenacia, with its lagoon facies at the upper boundary, in contact with the Dolomia Principale.

More specifically, the *Denti di Terra Rossa Formation* (Upper Ladinian) represents the postvolcanic Sciliar Dolomite, with horizontal stratification, inclined strata and blocks, still partly calcareous, at the foot of the coral reef. Locally it shows a reddish colour due to the internal sedimentation of red silt, and it heteropical with the Wengen and S. Cassiano formations. It crops out only at the northern boundary of the Sella Group, along a continuous W-E trending stripe that stretches from the Gardena Pass to Sura Sas. The outcrop consists of clearly visible inclined strata and blocks and it constitutes the vertical slope of the Sella Group facing the Colfosco valley.

Dolomia Cassiana (Lower Carnian) has different facies: a platform one, a massive one (close to the platform margin) and a well developed platform-scarp one (with inclined strata, breccias, megabreccias and arenites). It is heteropical with the S. Cassiano Formation and it has its upper limit in contact with the Heiligkreuz Formation. In the study area it crops out, with its platform facies, on the Setsas - Le Pale del Gherda, at Bosch d'Arparora, on the upper part of Monte de Lagazuoi and at the base of the sequence Dolomia Cassiana - Heiligkreuz Formations under Piz dles Conturines (Banch de Bisces). The massive facies essentially forms the basal portion of Monte de Lagazuoi. It also crops out at some limited areas near the Valparola Pass, at the base of the platform facies at Banch de Bisces, and west of Piz de Lavarela.

The *Dolomia Principale* (Upper Carnian - Norian) is a cyclic sequence of metre-thick dolomites, thin strata of stromatolites, loferites, levels of fine breccias and thin marly strata. In the study area it forms the upper portion of the Sella Group and of the Gherdenacia, the basal portion of the Sas dla Crusc, of the Piz de Lavarela, of the Piz dles Conturines and of the Zimes de fanes. Limited outcrops can be found in Valparola at Les Pizades and at Piz Ciampei.

Limestones and marls of Jurassic-Cretaceous age (1, 2)

The *Gardenaccia Formation* (?Pleinsbachian - ?Malm) is formed by greyish-green dolosparites, from medium to macro-crystalline, overlying with an erosive discontinuity the Dolomia Principale, generating lens-shaped bodies. At its base, thin strata of sharp edged dolomite breccias are present in many outcrops. In the study area it crops out extensively on the Gherdenacia, at Col da la Sone and at Forc. de Gherdenacia. A small outcrop can be found on the Sella Group, at Pizes dl Valun.

Rosso Ammonitico (Bajocian - Tithonian) is composed by pink to red nodular limestones, with *Bositra buchi*, gastropods, ammonites and echinoderms in the lower portion. The upper portion is dominated by red ammonitic limestones with reddish nodules of irregular form. It crops out in a limited area on the Sella Group, between Piz Boè and Piz Lech Dlace.

Puez Formation (Valanginian - ?Aptian) is composed by strata of marls and multicoloured micritic limestones, with silica nodules and thin strata, locally fossil rich and generally bioturbated. In the study the outcrops are very limited. They are present on the Gherdenacia, at Col da la Sone and near Forc. de Gherdenacia, and on the Sella Group, near Piz Boè, Lech Dlacc and south of Piz da Lech.

TECTONIC AND STRUCTURAL SETTING

The tectonic setting of the Alta Badia valley is the result of the deformation sequence that affected the wider dolomitic region. This sequence consists of four major phases: i) subsidence and fragmentation of the sedimentary basin that took place in the Upper Permian; ii) mesoalpine compression phase during the Upper Cretaceous - Lower Eocene; iii) neoalpine compression phase, from the Upper Oligocene to the Lower Miocene; iv) south-alpine compression phases during the Medium-Upper Miocene (Doglioni, 1984, 1987; Doglioni & Bosellini, 1987; Doglioni, 1990; Castellarin & *alii*, 1992).

Starting from the first important deformation phase, the Hercynian orogeny (Upper Sakmarian), the dolomitic region experienced different extensive phases, characterised by vertical movements that divided the area into a series of N-S trending basins with different subsidence rates. This favoured the formation of coral reefs and the accumulation of deep sea sediments (Leonardi, 1967).

The Triassic palaeo-geography was thus mainly controlled by extensive tectonics. Anyhow, also thrusts with a principal horizontal component occurred, which built a wide system of *enéchelon*- distributed overthrusts. Moreover, volcanic activity developed, responsible for the formation of volcanic and volcano-clastic sediments accumulating in deep basins and for the formation of the «line of Gardena Pass», a system of faults with an E-W trend.

The Triassic tectonics had a strong control on sedimentation. During the Anisian, two zones with different subsidence rates developed: the Badiota-gardenese structural height, corresponding to the Western Dolomites, and the Cadore basin, corresponding to the Eastern Dolomites (De Zanche, 1990). In the first zone, the stratigraphic sequence was reduced, while in the second one more complete sequences crop out. The complex palaeogeography was characterized by different depositional environments (deep-basinal, lagoon, tidal and continental).

During the Jurassic, extensive tectonics prevailed. The differential subsidence continued between the Cadore basin and the Badiota-gardenese platform, whose limit corresponded more or less with the current position of the Badia valley.

During the primary compressive phase (mesoalpine phase), dating back to the Upper Cretaceous - Lower Eocene, overthrusts and folds with N-S and NNW-SSE trending axes were formed (Doglioni, 1987; Zanferrari & *alii*, 1982). At the onset of Miocene the dolomitic region definitely emerged from the sea (Bosellini, 1996).

During the Neogene, the most important orogenetic phase took place: the neoalpine phase, which developed overthrusts and folds with E-W trending axes and right and left conjugate strike faults (Doglioni, 1987). The dolomitic region acquired its current ample synclinorium form, with an E-W trending axis, closed to the south by the Valsugana Line and to the north by the Funes Line. During that phase, also the metamorphic rocks forming the stratigraphic base were affected by the crustal shrinkage.

In the study area, the most significant structural elements from that deformation period are the synclines of the Sella Group and of the Gherdenacia, besides that of Gardena Pass (Engelen, 1963). Other structural elements are: the NW-SE trending strike fault on which Valparola is located and most of the faults that can be found on the Sella Group and on the Gherdenacia; the overthrusts of the Piz dles Conturines and of Falzarego Pass/Valparola Pass which caused the doubling of the stratigraphic sequence. In particular, the Piz dles Conturines overthrust seems to have reactivated a SW verging overthrust that originated during the previous mesoalpine phase (Bosellini & *alii*, 1996) (see the structural sketch reported in the geomorphological map annexed).

During the Pliocene and the Lower Pleistocene, uplifts and minor tilts affected the southern and eastern sectors of the Dolomites. From the Upper Pleistocene to the Holocene, the uplift of the area included an isostatic component due to glacier retreat. Many morphotectonic evidences demonstrate the activity, during that phase, of all disjunctive structures and, in particular, those NW-SE and NNW-SSE oriented ones that formed during the previous phase. Related to faults having different orientations are many large-scale landslides of prehistoric and historic time (Zanferrari & *alii*, 1982).

In the study area, two tectonic lineaments are present, which have been reactivated during the Pliocene and the Quaternary. The first one is the N-S trending fault that cuts the Sella Group along the Val di Mesdì; this fault has been considered active between 5.2 and 0.7 Ma B.P. by Carton & *alii* (1980), Zanferrari & *alii* (1982), Panizza & *alii* (1978), Slejko & *alii* (1989) and Castaldini & Panizza (1991). The second lineament is the right strike fault with a NNW-SSE trend along the Col Alt - Pralongià - Passo Incisa alignment. Its reactivation during the Pliocene-Quaternary period has been hypothesised on the basis of the alignment of congruous geomorphological elements such as mountain crest dislocations, fluvial bends and landslides affecting the Col Alt - Pralongià slopes among which the one reaching the village of Corvara in Badia (Corsini & Panizza, 2003).

GEOMORPHOLOGY OF THE ALTA BADIA VALLEY

Introduction

Landforms and processes in the Alta Badia valley are strictly controlled by the geological structure, both from the lithological and tectonic viewpoint. They reflect the modifications caused by exogenous forces, which shaped the relief during the different Quaternary morphoclimatic phases. The morphology of the area is characterised by mountain peaks with highly fractured vertical cliffs, separated by wide valleys with more gentle, undulated slopes. The most ancient traces left by geomorphological processes are of glacial origin and date back to the LGM. More evident and abundant are the traces left by the later pulses of valley glaciers during the Lateglacial, consisting of till deposits and moraine ridges whose elevation allows a qualitative reconstruction of the glaciers' evolution.

The intense jointing of the dolomite massifs, the pressure release related to glacier retreat, above all at valley junctions (Panizza, 1973), permafrost melting and the high relief energy have favoured the onset of rock fall and rock slides, sometimes reaching considerable extension. Periglacial processes, which still characterise the study area, have caused a significant production of cryogenic debris, which was also re-distributed in cones, protalus ramparts and rock glaciers by gravity, snow and ice. The availability of water from rain and snow melt - together with the poor geomechanical characteristics of the terrains outcropping in the middle and lower parts of the slopes - has favoured the onset of landslides, mainly consisting of earth flows and slides. Moreover rainfall, in particular if short and intense, has caused slope incision and debris flows, respectively on debris cones and at the valley bottom. Human activities, related to winter and summer tourism, on which the entire local economy is based, has led to important landscape modification in the last fifty years.

Structural landforms

The geomorphological map clearly shows how the general morphology of the study area is strongly conditioned by lithology, stratigraphy and tectonics and consequently by the differential erosion of outcropping formations. The slopes are, in fact, almost vertical where dolomitic rocks crop out, while they become less steep towards the valley bottoms, where rocks with abundant pelitic and/or clayey fraction crop out (figs. 3 and 4). Edges of structural scarps, frequently remodelled by degradation processes, border the upper portion of all dolomitic walls. Typical landforms due to differential erosion consist of structural terraces («cenge»), that can be found where terrains with a high percentage of marls and clays are in alternation with dolomitic strata. In particular, the most important structural terraces, although generally covered by extensive talus cones or scree, are located on the northern slope of the Sella Group and on the southern slope of Piz dles Conturines, where terrigenous-evaporitic sequences crop out.

Different systems of faults largely affect the Gherdenacia, the Sella Group and the area between the Valparola Pass and the Piz dles Conturines. They probably witness an extensive phase - likely to have occurred after the neoalpine compressive phase - and shape topographic profiles characterized by sub-parallel steps.

Moreover, along the north-western limit of the Monte de Lagazuoi - aligned to N-S trending faults - two highly jointed rock masses (Sas de Dlacia and Plan de Lot) are subject to rock falls and topples. Other highly jointed rock masses can be found at Crep de Sela, south-west of Corvara in Badia, again related to a clear N-S trending fault system affecting the eastern margin of the Sella Group.

A peculiar morphology is shown by the Pordoi Formation's outcrop at Crep da Munt (eastern slope of the Sella Group): the attitude of the strata is sub-vertical and it is due to the presence of an overthrust with a N-S trend (fig. 5).

Glacial landforms and processes

According to the findings of G.B. Castiglioni (1964) and previous researchers, during the LGM the Alta Val Badia, like all the other Dolomites' valleys, was almost completely covered by glaciers, being only the top parts of the mountain groups outside the ice masses (figs. 6 and 7).

The presence of ancient glaciers is proved by a series of landforms and deposits located mainly in the central-eastern sector of the study area. They correspond to frontal and lateral moraine ridges and till, often remodelled by gravitational processes or masked by soil and vegetation. The thickness of till varies from a few decimetres to more than one metre. Other pieces of evidence consist of erosion features, such as *roches moutonnées*, striated surfaces, hanging valleys and glacial cirques. The deposits are better preserved on both flanks of the San Cassiano valley and on the right flank of the La Gran Ega valley; the erosion landforms have been mainly recognized on the plateaus of the main mountain groups.

FIG. 5 - Vertical dolomite strata at Crep de Munt (Sella Group).

Erosion landforms

Among the erosion glacial landforms, the most frequent and best preserved in the area are glacial cirques, which are often located in correspondence of tectonic discontinuities. This is the case of the largest glacial cirques in the study area where small valleys were shaped along faults and overthrusts. That action has mainly deepened the valley bottoms and, secondarily, widened their cross section: therefore the major cirques have a longitudinal profile better developed than the transversal one. Examples are the cirques

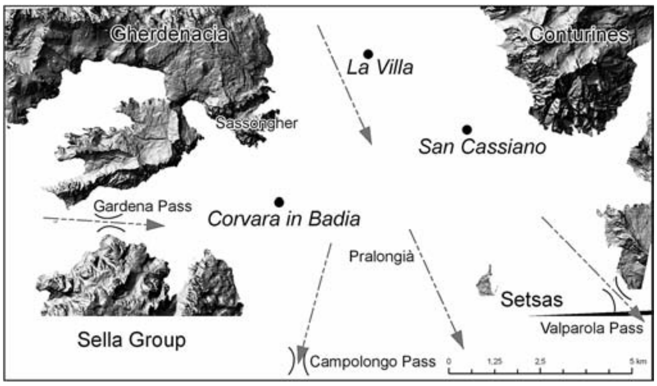


FIG. 6 - Extension and movement direction of ice masses during the LGM in the Alta Badia valley.

FIG. 7 - The Sassongher peak at Corvara in Badia. The clouds simulate the height reached by the ice masses during the LGM.

of the Val di Chedul and of Forcela di Sassongher, respectively at the western and south-eastern margins of the Gherdenacia; the cirque of the Forcela de Ciampei, north of Colfosco; the cirque of the Val Medesc, north-west of Piz de Lavarela; the cirques N-S trending of the valley that comes down from Forcela de Salares and Vallone Pudres, respectively on the Monte de Lagazuoi and on the Setsas, the cirque of the Val de Mesdì, on the Sella Group.

Where the cross section is reduced, cryogenic debris completely covers the rocky slopes underneath the cirque edges, often reaching the valley floor and masking the possible presence of glacial deposits.

All major cirques in the study area are also in connection with hanging valleys. This indicates the presence, during the termination of the LGM, of a network of glacier tongues within the main valleys that received secondary glacier tongues coming from tributary valleys. A spectacular case of hanging valley is that of Val de Mesdì - reaching Colfosco from the Sella Group - where the difference in level between the tributary and main valley bottoms is of about 200 m.

Frequent, but with much smaller dimensions, are the edges of glacial cirques occurring on the summit surfaces of the plateaus, up-valley of glacial erosion depressions. In many cases they show alignments along the direction of highest slope angle, with a step-like sequence. This is clearly visible on the eastern side of the Gherdenacia and of the Sella Group, in probable relation to the arrangement of the edges of the structural scarps.

Roches moutonnées, or rocks anyhow clearly modelled by the erosion of ice masses, characterise all summit surfaces of the plateaus of the Gherdenacia, Sella Group and Lagazuoi mountain groups. Where chemical weathering has not deleted them, striations show the preferential flow direction of glacial masses. This can be observed on the rock surfaces of the northern cliff of the Sella Group where striations show the movement direction of a glacier that, during the LGM, reached the Alta Badia valley from the Adige valley passing through the Gardena Pass. This provenance is also confirmed by the lithology of pebbles that have been found north of the Gardena Pass (see next paragraph). Similar erosion features have been recognised on the entire upper surface of the Setsas, from Pale del Gherda to the Valparola Pass. The smooth surface and the clearly rounded crest of the Setsas is likely to indicate the transfluence towards the Cordevole Valley of the glacier coming from the San Cassiano valley. The processes which caused the above mentioned erosion landforms, are interpreted as related to the maximum expansion of LGM's ice masses, when the general flux direction of the alpine glacial cap was from the alpine axis towards south.

Accumulation landforms and deposits

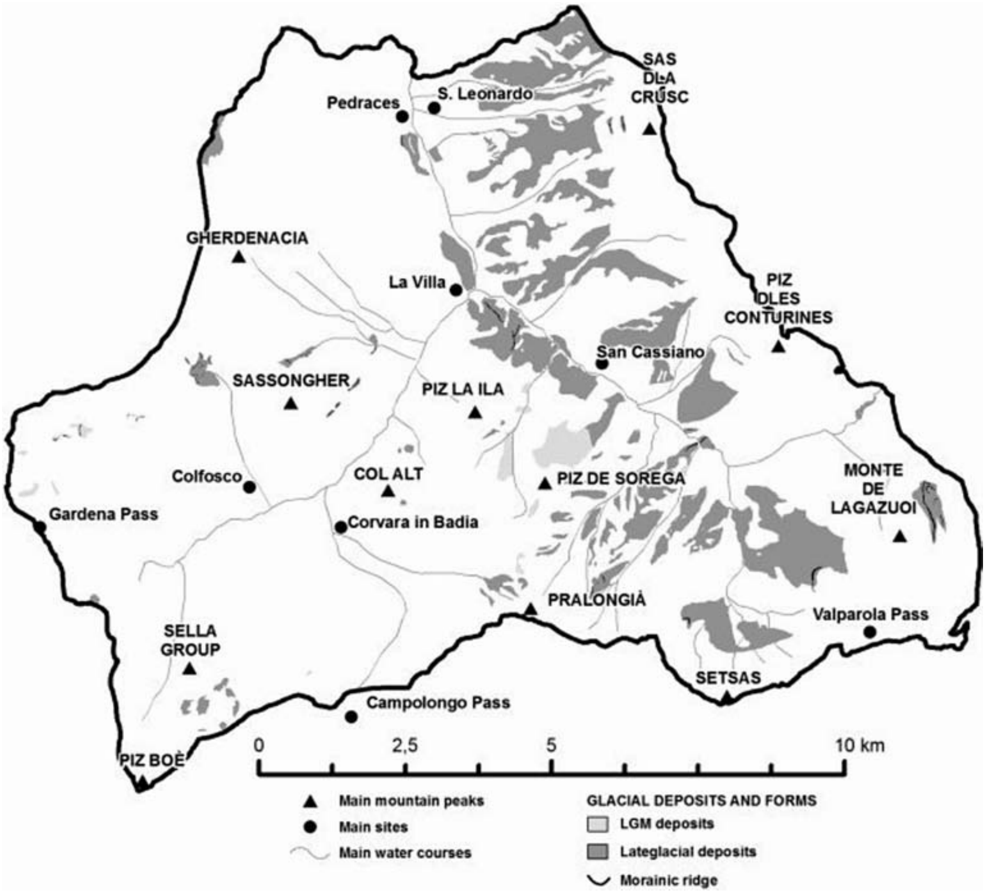
In general, glacial deposits mainly occur on the flanks of the San Cassiano and La Gran Ega valleys, though largely dissected by slope processes (fig. 8). They are characterised by accumulations of dolomite blocks and, secondarily, of arenitic and calcarenitic ones, included within a silty-clayey matrix, originated from the most frequently outcropping terrains. Generally, the dolomite blocks show a wider range of grain size values with respect to the debris derived from other lithotypes.

The distinction between LGM and Lateglacial deposits has been performed based on i) the dimension of dolomite blocks, ii) the degree of rounding and the percentage of finer sediment and iii) the possible presence of clasts of rocks not outcropping in the study area. The distinction was quite complex since almost all deposits are masked by soil and vegetation and it has rarely been possible to examine natural sections. In addition, it should be emphasised that in the study area the degree of rounding of clasts cannot always be considered as an evidence of long-lasting glacial transport and, therefore, related to periods of large extent of glacier masses. Actually, a remarkable degree of rounding of dolomite blocks could also be related to prolonged exposure to chemical weathering, mainly solution.

LGM landforms and deposits are present in scattered accumulations in the study area, mainly on the Pralongià plateau (figs. 4 and 9); they normally consist of dolomite blocks of sub-metre dimensions, highly rounded and often included in fine matrix, and of erratics in agreement with previous authors, the provenance of LGM ice masses is assumed to be from the north, that is from the Pusteria Valley (through the Badia Valley) and from the Adige Valley (through the Gardena Valley) (fig. 6). This is confirmed by the finding, within the glacial deposits, of clasts of lithotypes that do not outcrop in the Alta Badia valley or that outcrop in different mountain groups with respect to those where they were found. Actually, pebbles from the Rosso Ammonitico, which is outcropping on the Gherdenacia, were recognised in glacial deposits found on the Pralongià, at the Rü dla Frëina (west of San Cassiano), at some 1800 m of elevation.

Small metamorphic pebbles were found in glacial deposits referring to the LGM north of the Gardena Pass - along the western limit of the study area, at an altitude of 2240 m. They witness the transfluence of ice masses from the Gardena valley to the Alta Badia valley during the LGM.

FIG. 8 - Sketch map of glacial deposits and landforms in the Alta Badia valley.



Moreover, clasts of phyllites have been found south-east of Forcela de Ciampei (north of Colfosco).

Worth of notice, since they are unique forms in the area from the LGM period, are two parallel lateral moraines located on the right flank of La Gran Ega valley, at an altitude between 2000 and 2200 m, east of Píz dl Zübr. They have been assigned to a late phase of the LGM due to their altitude, and their genesis interpreted as glacier-contact.

FIG. 9 - Dolomite erratic boulder on the Pralongià plateau, witnessing the presence of a glacier cap during the LGM. On the background, the west facing profile of the Setsas.

During the Lateglacial - whose onset can be placed at around 15,000 cal BP (Orombelli & Ravazzi, 1996) - after the relatively rapid shift towards less severe climatic conditions, the alpine glacier cap underwent a progressive reduction and subdivision into valley glaciers.

Thus the main flow direction of LGM ice, from the north to the south, reverted: glaciers started to flow along the profile of the main valleys: from south-east to north-west in the San Cassiano valley, from south-west to north-west in the Corvara in Badia area and from south to north in La Gran Ega valley. Frontal moraines, partially preserved in the San Cassiano and Valparola valleys, prove this flow inversion.

It should be noticed that evidence was found that the upper part of the Pralongià plateau was already ice-free during the Lateglacial, as witnessed by the dating of a charcoal sample taken from an excavation made close to Piz de Surega, at a height of 1937 m. This sample was dated back to 16,610 cal BP (B-267137) showing that at least the central sector of Alta Badia valley was ice-free already at that time.

Lateglacial landforms and deposits, mainly found on the eastern sector of the study area, show dolomite blocks with diameters larger than one metre, less rounded, and mixed inside a less fine matrix than that of LGM deposits. Lateglacial landforms consist of frontal and lateral moraines whose integrity is often compromised by subsequent fluvial erosion or slope processes. Deposits are mainly related to ablation till that experienced just a small transportation by rapidly retreating valley glaciers.

South of the village of Pedraces, on the left flank of the La Gran Ega valley, a lateral moraine proves the presence of a glacier tongue hosted in the valley; the proximity of the ridge to the valley bottom leads to hypothesise a rather thin thickness of the glacier at that position.

Although G.B. Castiglioni (1964) mapped a frontal moraine at the village of Pedraces, geomorphological survey and mapping have led to interpret the form as part of the rockfall/ rock-avalanche accumulation that reaches the village from the Gherdenacia.

At La Villa, on the left flank of the La Gran Ega valley, the presence of glacial deposits has been revealed by some excavations pits. The deposits have not been substantially remodelled by gravitational or fluvial processes. The absence of any moraine ridge could not allow to attribute the deposit to the Lateglacial; nevertheless, it has been assumed that at least the upper part of those deposits is from that period, assuming that Lateglacial deposits in valley bottoms should anyhow overlie LGM ones (if any).

Upstream La Villa, on the left flank of the San Cassiano valley, three lateral moraines ridges are present, at a mean altitude of some 1500 m, marking the stadial advance of the glacier tongue hosted within the San Cassiano valley. On the opposite slope no lateral moraines can be found, since they were probably deleted due to more frequent and intense gravitational processes.

Among the better-preserved landforms are seven frontal moraines, NE-SW trending - located at L'Armentarola in the San Cassiano valley - which are made up of large dolomitic blocks, often round-shaped, mixed within a fine matrix. The length of the arc segments varies from 50 to 400 m, but their original extent has been partly masked by debris accumulated by different gravitational processes. According to G.B. Castiglioni (1964), those arcs should correspond to frontal «intermediate moraines» built between two Lateglacial phases (not specified by the Author).

A well-preserved frontal moraine stretches for 400 m at the northern limit of the Vallone Püdres (at Setsas), completely covered by vegetation. It shows a NW-SE direction and it marks the limit reached by a small glacier of the Gschnitz stadial (G.B. Castiglioni, 1964) hosted within the valley.

Several E-W trending ridges, composed by clasts of different lithology and grain size, among which also dolomitic blocks larger than one metre, can be found along the hiking path no. 18, near Malghe Valparola, in the central part of Valparola. This is likely to be a thick glacial deposit, preserved by the erosion of the torrent, which G.B. Castiglioni (1964) referred to within the Sciliar stadial phase.

A series of concentric ridges, NE-SW trending and some 400 m long, can be found at the northern limit of Prei Glira, west of Monte de Lagazuoi. They are composed by large dolomite blocks, with evident karst features and in great part covered by vegetation. Uphill, a back-arc plain has developed, formed by fine colluvium transported by running waters and by coarser debris coming from the debris cones at the western foothills of the Monte de Lagazuoi.

Dolomite blocks similar to those mentioned above cover the entire valley down to Malghe Valparola. It is likely that this large accumulation (some 76,000 square metres) corresponds to ablation till consisting of debris provided by one or more rock falls which reached the surface of a valley glacier. The concentric arcs observable in the highest sector of this glacial deposit may refer to the last advance of the glacier, before its final retreat.

At the south-eastern limit of the study area, on the Monte de Lagazuoi plateau, between Cima Scotoni and Piza Sud, a moraine system is present, formed by two lateral moraines converging towards three concentric frontal moraines. The eastern lateral moraine is partly masked by coalescent debris cones.

A series of partially stratified deposits outcropping at the foothill of the Conturines Group (e.g., above the village of San Cassiano and at the base of the Sas dla Crusc) have been interpreted as of ice-margin accumulation. Though they should be therefore considered as paraglacial deposits rather than glacial ones, they have anyhow been mapped as glacial since they are largely overlapping and intermingled with glacial deposits, making their distinction often questionable.

Excavations carried out for building purposes along the Rü Giaric, at San Cassiano, revealed the presence of possible proglacial deposits, composed by very sparse and small dolomitic blocks within an abundant fine matrix. Their depositional environment seems to be that of a proglacial lake which probably formed after the damming of the valley by frontal moraines. Due to the very limited extent of the deposit, it was not possible to outline it in the geomorphological map.

Glacial deposits have been also found above the village of Colfosco, at the foot of the cirque of Forcela Ciampei. They consist of a series of well-preserved moraine ridges which are also responsible for the formation of the Lech de Ciampei (fig. 10).

FIG. 10 - Frontal moraine ridge within a glacier cirque at Lech de Ciampei. In the centre the Sassongher peak.

Periglacial landforms and processes

Since the last phases of the LGM, periglacial processes became increasingly important for the shaping of the relief of the Alta Badia valley. Among those, *frost shattering* processes which caused significant production of debris, generally making up widely diffused scree slopes and talus cones. The debris was then made available for mobilisation or transportation by gravitational and torrential processes and, secondarily, by other cryogenic processes. The abundance of debris varies within the different sectors of the study area, depending on the type of rock affected, on the fracture density in the rock massifs, on slope orientation and on the presence of water seeping through the rock fractures.

The geomorphological map clearly shows how gravitational processes were, and still are, the main cause of cryogenic debris redistribution. Other cryogenic processes had a far minor role in debris mobilisation, proved by the scarce spatial frequency of related landforms, such as protalus ramparts and rock glaciers.

More difficult is to estimate the contribution to cryogenic debris redistribution by *snow avalanches*: although being a recurrent processes in the area (Ghinoi & Chung, 2005), snow avalanches did not gave origin to specific landforms and deposits. More likely, snow avalanches have always acted marginally, above all with respect to other gravitational processes, producing hardly distinguishable morphological changes: this can be due to a low frequency of occurrence and/or due their mainly superficial type. Chrono-stratigraphic data analysed in the Pescosta area (Borgatti & *alii*, 2006) have highlighted a reduced sedimentary contribution by snow avalanches also during the earlier phases of the Holocene.

The few *protalus ramparts* recognised in the area are mainly located within glacial cirques such as those in Val di Chedul (Gherdenacia Group), at Piz Boé (Sella Group), at the large cirque of Monte de Lagazuoi and on the Setsas. Besides those located within glacial cirques, three other protalus ramparts were identified at Piz Ciampei - west of the Valparola Pass - and a large one just under the Kreuzkofel, at the north-eastern limit of the study area; some small ones are finally located on the northern structural terrace of the Sella Group. Protalus ramparts in the study are generally inactive, except for the one at Piz Boé (2900 m). This proves how currently, except at the highest elevations, snow and ice have a minor persistence on the ground with respect to the past, also on slopes with favourable conditions for snow pack conservation, such as those with west and north orientations. The festooned shape of some protalus ramparts, in particular those located on the Monte de Lagazuoi and in Val di Chedul, lead to hypothesise an incipient evolution, towards more rock-glacier-like landforms (i.e., protalus rock glaciers). A peculiar example of protalus rampart is that located west of Kreuzkofel, at the base of an inactive rock fall deposit. Its almost continuity with the lateral moraine located some metres to the south could lead to hypothesise a glacial genesis, but its shape, markedly concave uphill, suggested a periglacial genesis. Considering the deposits uphill, it is likely that the protalus rampart formed after at least one rock avalanche occurred on an ice surface; this could also justify the considerable distance reached by the debris accumulation, far longer than that of all other protalus ramparts of the area.

Only two *rock glaciers* can be found in the area: an inactive one near the Valparola Pass and an active one north-west of Piz Boé. The first one is made of a debris accumulation consisting of large dolomitic blocks, probably detached from the south-western flank of Monte de Lagazuoi and deposited on an ancient glacier or ice field. The finer matrix inside is visible at road cuts along the provincial road. The deposit has a tongue-like shape and its surface ripples and counterslopes can be detected. Some morphological evidence confirm its inactivity: the tip of the tongue and the lateral flanks have small slope angles; during summer, no springs are present at the margins, proving the absence of internal ice; finally, the road-cut generated scarps are quite stables.

Opposite morphological evidence, such as the high slope angles of frontal and lateral flanks, to consider as active the rock glacier at Piz Boé. The altitude of 2900 m is coherent with the lower elevation limit for ground-ice persistence (2400 m) identified by Carton & *alii* (1988) and by Guglielmin & Smiraglia (1997) for the activity of rock glaciers within the dolomitic area.

Gravity-induced slope landforms and processes

Gravity-induced slope landforms and processes are the most recurrent geomorphological feature within the Alta Badia valley. Particularly frequent and active since the end of the Lateglacial, after the retreat of the valley glaciers, gravitational processes produced landforms that strongly characterise the current morphology of the area.

Scree slopes, talus and talus cones, essentially related to cryogenic processes acting on densely fractured rock cliffs, encircle the foothills of the main mountain groups and peaks.

Evidence of slope instability can be found both on the dolomite cliffs and on the less steep slopes composed by marly and clayey terrains. In particular, rock falls, topples and rock slides prevail in highly fractured dolomite rocks, while earth flows and earth slides mainly affect the terrains underneath, such as those of the S. Cassiano and Wengen formations. The latter formations are also affected by solifluction which determines the formation of lobes, ripples and extensional cracks in soil. The high frequency of intense precipitation events favour debris flows, which mobilise the debris making up scree slopes and talus cones. Surficial movements and deformations, due to subsurface water, are common on terrains showing a plastic mechanical behaviour, in particular where topography alternates concavities to convexities, respectively favouring soil saturation and its slow mobilization.

Landslides cover the 26% of the study area. In particular, earth flows and/or earth slides are the most diffuse (17.6%), showing the highest concentration and activity in the central-southern sector, between Corvara in Badia and Valparola. Rock slides make up 5% of the total. Although far less frequent in number than earth flows and slides, they show a higher extent per unit. Almost all inactive, rock slides are located at the base of all main dolomite massifs. Rock falls represent 3.2% of the total area. They are widely diffused at the foothills of the dolomite massifs.

As demonstrated by radiocarbon dating (Soldati & *alii*, 2004; Borgatti & Soldati, 2010), the first phase of high slope instability of the Corvara landslide dates back to the Preboreal and Boreal (some 11,500-8500 cal BP), just after the end of the Lateglacial (tab. 1). During this period large translational rock slides and complex movements (rotational slides and flows) affected the dolomite slopes following the withdrawal of the LGM glaciers, whilst rotational slides and flows affected the underlying pelitic formations probably favoured by high groundwater levels due to an increase of precipitation and/or permafrost melting. A second concentration of landslide events occurred during the Sub-boreal (about 5800 to 2000 cal BP), when slope processes mainly ascribable to rotational slides and/or flows took place in both the study areas. It is likely that the events dating back to this period are mainly reactivations of older events due to increased precipitation that characterised several European regions during this mid-Holocene period.

TABLE 1 - Radiocarbon dates of landslide and landslide-related deposits in the Alta Badia valley; data calibrated with Calib. 4.1 (Stuiver & Reimer, 1993), data set by Stuiver & *alii* (1998) (after Soldati & *alii*, 2004; modified)

Landslide name	Landslide type	Sample code	Sample type	Site of collection	Depth *(m)*	Conventional Age *(^{14}C yr BP)*	Calendar Age 2σ *(Cal yr BP)*
Corvara	earth slide - earth flow	B-112032	wood	borehole	25.70	8820 +/– 50	10,152 - 9632
Corvara	earth slide - earth flow	B-112032	wood	borehole (C1)	25.70	8820 +/– 50	10,152 - 9632
Corvara	earth slide - earth flow	B-112033	wood	borehole (C1)	26.40	8560 +/– 90	9709 - 9334
Corvara	earth slide - earth flow	B-112031	organic sediment	borehole (C3)	22.70	7920 +/– 70	9009 - 8543
Corvara	earth slide - earth flow	B-154704	wood	borehole (C6)	69.70	8020 +/– 60	9030 - 8650
Corvara	earth slide - earth flow	Ki-9233	wood	borehole (C6)	47.50	5543 +/– 72	6471 - 6199
Corvara	earth slide - earth flow	Ki-9230	wood	borehole (C6)	19.10	4616 +/– 64	5575 - 5052
Corvara	earth slide - earth flow	B-112029	wood	borehole (C2)	7.50	4260 +/– 70	5025 - 4575
Corvara	earth slide - earth flow	B-112030	wood	borehole (C2)	20.00	4260 +/– 70	5025 - 4575
Corvara	earth slide - earth flow	Ki-9234	tree trunk	erosion scarp	8.00	3888 +/– 64	4513 - 4094
Corvara	earth slide - earth flow	B-105976	tree trunk	erosion scarp	6.00	3830 +/– 60	4417 - 3999
Corvara	earth slide - earth flow	B-105977	tree trunk	erosion scarp	4.50	2860 +/– 60	3207 - 2792
Corvara	earth slide - earth flow	B-93975	tree trunk	erosion scarp	5.00	2490 +/– 60	2750 - 2352
Corvara	earth slide - earth flow	B-112034	wood	borehole (C4)	37.40	2260 +/– 50	2351 - 2129
Arlara *(SE of Corvara)*	earth slide - earth flow	B-105975	tree trunk	erosion scarp	3.5	6870 +/– 50	7789 - 7592
Col Alto	earth flow - mud flow	B-93976	tree trunk	excavation	2.00	2350 +/– 60	2708 - 2183
Rio Pocol *(SE of San Cassiano)*	earth flow	B-128367	tree trunk	erosion scarp	5.00	950 +/– 50	954 - 736
Colfosco	rock fall / avalanche	B-112024	tree trunk	excavation	3.50	4420 +/– 70	5030 - 4978
Colfosco	sedimentation in dam lake	Ki-9232	organic sediment	borehole (S4)	15.10	7088 +/– 72	8106 - 7751
Colfosco	sedimentation in dam lake	B-154701	wood	borehole (S3)	12.80	6810 +/– 60	7700 - 7560
San Cassiano	earth flow	B-128365	tree trunk	excavation	3.50	2260 +/– 60	2869 - 2715
San Cassiano	earth flow	B-128366	organic sediment	excavation	7.40	2610 +/– 60	2845 - 2496
San Leonardo	earth slide - earth flow	B-128368	wood	borehole (SL2)	11.00	4890 +/– 70	5839 - 5475
Col Maladët	rock slide *(begin of dam lake sedimentation)*	B-112026	wood	borehole (B5)	20.20	9080 +/– 70	10,401 - 10,154
Col Maladët	sedimentation in dam lake	B-112028	wood	borehole (B6)	20.24	8810 +/– 70	10,173 - 9557
Col Maladët	sedimentation in dam lake	B-112025	wood	excavation	5.64	7740 +/– 80	8696 - 8386
Col Maladët	sedimentation in dam lake	B-112027	wood	borehole (B6)	4.40	6460 +/– 90	7563 - 7213
Col Maladët	sedimentation in dam lake	B-112023	wood and peat	excavation	4.20	3550 +/– 70	4075 - 3640
Col Maladët	sedimentation in dam lake	B-112022	wood	excavation	1.43	3210 +/– 60	3626 - 3272
Col Maladët	sedimentation in dam lake	HD-19408	wood	excavation	0.48	1249 +/– 22	1263 - 1090
Col Maladët	debris flow	B-154705	organic sediment	excavation	3.50	1320 +/– 60	1320 - 1100
Col Maladët	debris flow	Ki-9229	chalk	excavation	5.00	1281 +/– 64	1306 - 1058
Col Maladët	debris flow	Ki-9231	tree trunk	excavation	6.00	2537 +/– 64	2771 - 2359
Col da Oi	earth flow	Ki-7757	tree trunk	erosion scarp	2.00	3050 +/– 50	3363 - 3079
Greif-Pescosta	earth flow - mud flow	Ki-9226	tree trunk	excavation	3.50	1490 +/– 64	1525 - 1288
Greif-Pescosta	earth flow - mud flow	B-154703	peat	excavation	3.30	810 +/– 60	900 - 660
Greif-Pescosta	earth flow - mud flow	B-154702	peat	excavation	2.80	340 +/– 60	510 - 290
Greif-Pescosta	earth flow - mud flow	Ki-9227	organic sediment	excavation	2.50	378 +/– 64	529 - 298
Stella Alpina *(N of Colfosco)*	debris flow	B-154706	organic sediment	excavation	5.00	1950 +/– 60	2030 - 1800
Sottocianin *(E of La Villa)*	rock slide - earth flow	Ki-9228	tree trunk	excavation	2.50	8143 +/– 72	9398 - 8814
Gardena Pass	rock slide	R99-1258	surface exposure dating by cosmogenic 36CI AMS measurement in dolomite rock from the main scarp			from about 11,800 to 8500 yr BP with erosion rates from 20 to 10 mm/ka respectively	

The recurrence of landslide activity has certainly been influenced also by non-climatic factors, in particular structural ones. First of all the spatial distribution of geological formations with different mechanical characteristics must be taken into account. In particular, the occurrence of landslides is high where rigid and resistant rocks (e.g., dolomites) showing brittle behaviour, overlie weaker rocks characterised by ductile behaviour (e.g., marls and clays). Furthermore, also where the effects of tectonics were most intense, in correspondence with faults or overthrusts, mass movements have been favoured.

Rock falls

Rock-fall deposits are widely distributed in the study area. Their extent can be significant, especially where rock falling was followed by rock/debris avalanches which could increase the runout of the displaced mass. The deposits are generally made up of blocks with extremely various diameters, chaotically distributed along the slope. Typical source areas are the dolomite cliffs. Most of the deposits are almost completely covered by shrubs and trees. The causes of such mass movements can be different, acting singularly, in combination or in sequence: i) retreat of ice masses and subsequent lack of support to rock walls, locally intensely affected by tectonic joints; ii) permafrost melting; iii) earthquakes etc.

Among the most evident rock-fall accumulations, worth of notice are those on which the villages of Colfosco and Pescosta were developed. The Colfosco source areas are quite far from the accumulation areas, leading to hypothesise a rock avalanching phenomenon. The landslide has been dated 5000 cal BP thanks to the finding of a tree trunk in an excavation, at a depth of 7 m inside the rock-fall deposit. However, rock-fall events could have been active even before, as it was suggested by the 7000 cal BP dating of organic lake sediments (typical of sedimentation occurring in a landslide dammed lake) extracted from a borehole uphill the landslide (Soldati & *alii*, 2004).

Coalescent rock-fall deposits can be found at the base of the rock slide next to the Gardena Pass, on the left flank of the Rü de Pisciadù valley. In this case, the rock-fall events have to be related to the extreme instability of the dolomite rock mass displaced by the rock slide.

Along the north-eastern margin of the Gherdenacia Group - at the northern limit of the area - two coalescent rock-fall deposits are located on the slope reaching La Gran Ega torrent; the village of Pedraces is located right on the foot of the southernmost deposit, which was partly considered as a glacial landform (moraine arc) by previous Authors (e.g., G.B. Castiglioni, 1964). There, instability of the rock mass is due to the presence of a weakness zone caused by the vertical right-strike neotectonic fault described above. The same structural cause is hypothesized also for the large rock-fall deposits identified along the northern slope of the Sella Group, at Font. Pera Lada: the source area is crossed by two conjugate faults (NNW-SSE and NNE-SSW trends) affecting the entire massif base composed by Dolomia Cassiana.

A large rock-fall accumulation can also be found from Plan de Lot to Rü Sciarè, in the eastern sector of the study area. The instability of the Dolomia Cassiana, from which the rock fall was detached, is caused by the presence of a clear N-S trending fault system responsible for the displacement of rock masses in the north-western sector of the Monte de Lagazuoi (Sas de Dlacia and Salares) and at Piz dles Conturines (Plan de Bisces and Piz Armentarola). In this case, the rock-fall deposit lies at the junction between three valleys that hosted glacier tongues: the one coming from the Setsas, the one on the plateau of Monte de Lagazuoi and the one coming from del broad basin of Le Gran Plan, reaching the area through the Col de Locia. Therefore, it is possible that a predisposing factor to rock falling was the pressure release after the retreat of ice masses («confluence glacio-pressure», according to Panizza, 1973).

In the same area, it is worth mentioning a trock toppling related to the structural condition mentioned above: two rock pillars were detached from the Sas de Dlacia, on the western flank of the Monte de Lagazuoi, close to two N-S trending fractures. The detachment seems to have occurred as a backward toppling (Dikau & *alii*, 1996) favoured by deformation processes affecting the underlying terrains of the S. Cassiano Formation.

Minor rock-fall deposits are located at the base of the dolomite cliffs of Sas dla Crusc, Monte de Lagazuoi, Setsas and Piz Ciampei. Structural factors, related to the local minor joint systems, play a significant also in this case.

Recent rock falls - whose accumulation extent is too small to be depicted in the geomorphological map - detached from mountain peaks higher than 2300 m on the Gherdenacia (e.g., at the peaks of Cier, Summer 2004, and Sas Ciampac, Spring 2005; fig. 11). This can be interpreted as the consequence of the thawing of permafrost trapped in the fossil state within rock discontinuities (Panizza, 2009b).

Rock slides

The rock slides recognised and mapped in the study area are generally of considerable size and volume involved. The predisposing factors can be related to structural features, in particular to the presence of tectonic joints and to the stratigraphic framework. The overposition of highly fractured dolomite formations on the basinal formations underneath - which may assume a visco-plastic behaviour - favoures water concentration and infiltration, increasing the neutral pressures inside the marly-clayey terrains.

Other factors related to morphoclimatic conditions may have played a secondary role, increasing the frequency of occurrence of those landslide types. In fact, some periods record an increase of events which can be related to the following causes: pressure release after glacier retreat, increase of precipitations and melting of permafrost.

North-east of the Gardena Pass, the largest and most spectacular rock block slide in the study area can be found, the Gardena Pass landslide. This is a complex-composite-type mass movement extending over an area of about 1.4 km^2. It started as a rock block slide affecting dolomite rock

FIG. 11 - Evidence of the rock fall occurred at Sas Ciampac (Gherdenacia Group) during Spring 2005.

FIG. 12 - Gardena Pass rock slide.

types and evolved into a rotational slide affecting weak clayey rocks of the S. Cassiano and Wengen formations, finally turning into an earth slide - earth flow of some million m^3 of clay-rich material. Boreholes and a geophysical survey have shown that the thickness of the earth slide - earth flow portion ranges from 45 to 70 m (Borgatti & *alii*, 2004). Along its entire length, the edge of the main scarp crosses the outcrop of Dolomia Cassiana, tracing an arc-like line concave uphill. The ^{36}Cl datings of dolomitic rock surfaces have allowed to date the origin of the rock block slide back to 10,000 cal BP, although the result has ample uncertainty margins (Soldati & *alii*, 2004). The great dolomite rock mass detached by its outcrop is extremely dissected and its mobilization, along a deepsliding surface, caused inner topples and rock falls (fig. 12). The uppermost rock block slide does not show evidence of activity, whereas large sectors of the deposit affected by flow are active, causing damages to the roadway connecting the Alta Badia valley with the Gardena Valley.

Other rock slides - mainly of rotational type - affect the terrains of the Wengen Formation, on the left flank of the Rü de Pisciadù valley, between the above mentioned landslide and the village of Colfosco. The edge of its scarp is located at the base of the rock wall of Dolomia Cassiana and the boundary between the rocks of the Wengen Formation and the volcanic and volcano-clastic rocks underneath.

Of peculiar interest, regarding the geomorphological evolution of the Corvara in Badia area, are the landslides affecting the left flank of the Rü de Pisciadù valley, between Pescosta and Vorda, at Col Maladët: they were, in fact, able to dam the valley for more then once, starting from some 9000 cal BP (Corsini & *alii*, 2001; Soldati & *alii*, 2004; Borgatti & *alii*, 2006).

Aligned along a NNW-SSE direction are two rock slides at the base of the dolomitic wall (Dolomia Principale) of Sas dla Crusc, at the north-eastern limit of the area. To the south, the normal fault crossing the nearby Val Medesc has the same direction. Also in that case, tectonics appear to be the preparing condition for the origin of the slides. There, the evolution of the mass movements (rock falls, earth slides and earth flows) and the form of the source area make the instability framework very similar to that of Gardena Pass.

Close to the village of San Cassiano, a large rotational rock slide affects the right flank of the Rü Giaric, at Prada. The edge of the scarp corresponds with the south-verging thrust of the Piz de Lavarela; the toe is near the road between San Cassiano and La Villa. To be noted is the alignment, along the presumed continuation of the thrust towards west, of other edges of earth-slides and earth-flow scarps: the water seeping through the cracks systems within the dolomite massif above preferentially concentrate along that alignment, favouring the persistence in time of neutral pressures in the terrains of the S. Cassiano Formation underneath.

Also the two rock slides, specular with respect to the mountain crest of Les Pizades, adjacent to the Setsas, seem to be favoured by tectonics. Les Pizades crest, in fact, shows steep slopes on its eastern and western flanks, both of them trending N-S: a proxy to hypothesise a fault system similar to that of the nearby western flank of Monte de Lagazuoi, visible at best at Sas de Dlacia. In particular, within the western landslide body, concave-uphill concentric arcs, are present, together with many counterslopes that lead to hypothesise a multiple rotational sliding surface.

Earth flows and earth slides

Earth slides and earth flows are the most recurrent mass movements in the area. Since they are often related in space and time - which makes their distinction quite questionable - earth slides and flows have been depicted with the same symbol in the geomorphological map. Both landslide types affect almost exclusively the terrains of the Wengen and S. Cassiano formations often giving rise to landslides of complex and/or composite style, such as that of Corvara in Badia which makes up the most relevant example of mass movement in the study area, also for its hazard implications.

Earth slides are normally deeper than earth flows and they often show multiple sliding surfaces. Flows frequently affect silty-clayey terrains of surficially weathered rocks or preexisting landslides, usually after prolonged precipitation or after the snow melting. They do not show well-defined sliding surfaces and the accumulation zone is generally characterised by rather flat lobes. When slides and flows occur jointly, the typical feature is that of rotational earth slides in the upper parts of the slopes and earth flows in the medium and lower sectors.

The highest distribution of these mass movements occurs along the western and northeastern sides of the Pralongià - Piz la Ila mountain crest - where they largely show a retrogressive dynamics - and along the western slopes of the Sas dla Crusc and of the Piz de Lavarela. Less frequent and mainly consisting of earth flows, are the landslides occurring on the left and right flanks of the Rü de Pisciadù, from the Gardena Pass to La Villa.

The orientation of the main landslide bodies leads to hypothesise a tectonic control. In particular, the earth slides and flows affecting the Pralongià plateau show tracks with a SW-NE trend, which is related to the Neogene SW-NE fault system.

For earth slides and flows, the state of activity has been deduced by the analysis of multitemporal aerial photographs, by detailed analysis of morphological, drainage and vegetation evidence. Among them, 31% have been assessed as active. In any case, for great part of inactive bodies a future reactivation cannot be excluded (even in the short period), since the driving forces are still present and active within the current morphoclimatic conditions: mainly the availability of precipitation and snow-melting water.

At present, the reactivation of portions of inactive landslides is a recurrent process. This is often related to lateral erosion by torrents or to the retrogressive movement of scarps. This is not necessarily leading to the entire remobilisation of the landslide.

As mentioned above earth flows and earth slides may occur in combination, in temporal sequence or simultaneously, giving rise to complex and/or composite movements.

An outstanding example is provided by the Corvara landslide (fig. 13) which can be considered as both a complex- and composite- style movement. In-depth investigations carried out on the landslide, including geomorphological survey, geotechnical and geophysical tests, monitoring of displacements and material dating, have provided a detailed and precise model of the kinematics and evolution of the landslide, as well as of its hazard implications (Corsini & *alii*, 1997; Corsini & *alii*, 1999; Corsini & Soldati, 2004; Corsini & *alii*, 2005). The landslide consists of rotational/translational earth slides and earth flows.

FIG. 13 - The accumulation zone of the Corvara in Badia landslide, bordered by Rü de Dlijia (on the left) and Rü Tort (on the right).

Dating of organic material found within the landslide deposit showed that the movement was active at least since some 10,000 cal BP, with a retrogressive evolution that drove the source areas to a position which is currently very proximal to the Pralongià - Piz La Ila mountain crest. The landslide was probably active or dormant throughout the Holocene, showing periods on increasing activity due to changing climate conditions (Soldati & *alii*, 2004; Soldati & Borgatti, 2009; Borgatti & Soldati, 2010). The depth of the present-day major active sliding surfaces ranges from 48 m (in the thickest part of the accumulation area) to about 10 m (Corsini & *alii*, 2005). Displacement rates generally range from 0.1 to > 1.7 m/year (fig. 14), being the movement faster in the track area. Flows are particularly active within concave slopes at the source areas and they normally affect the surficial part of previously slid terrains. Within the accumulation zone, slides and flows are also caused by the lateral erosion of the landslide body provided by the Rü Tort (Rio Torto) and Rü de Dlijia (Rio Chiesa), which cause severe damages to the road connecting Corvara in Badia to Campolongo Pass and to the ski-lifts (fig. 13).

It is worth recalling the earth slides and earth flows which are part of the Gardena Pass landslide (see «rock slides» section) which were triggered by the huge rock block slide which affected dolomite rock cliffs of Gherdenacia. Recent monitoring data from inclinometers have shown that movements in the earth flow portion take place at about 20 m in depth. The lower part of the landslide body is instead more stable. Seismic data actually showed the pres-

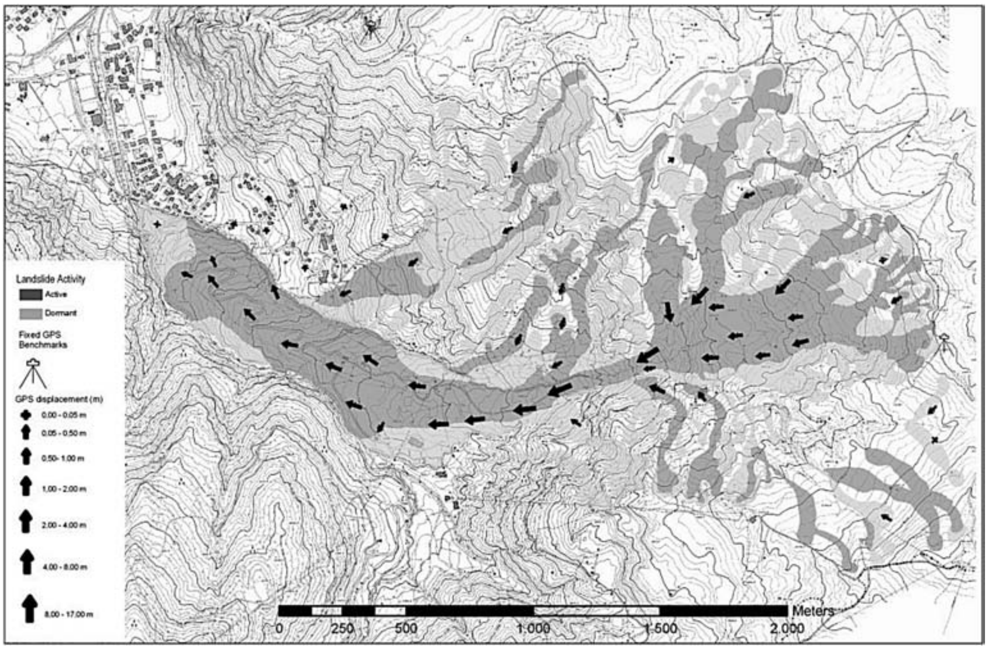


FIG. 14 - Average movement rate of the Corvara in Badia landslide in the period 2001-2010, obtained by means of GPS measurements.

ence of a 30 to 50 m thick level of fluvio-glacial gravel; this level probably acts as a natural drainage system, preventing the steeper portions of the earth flows from being active with higher displacement rates (Borgatti & *alii*, 2004).

Along La Gran Ega valley, in the northern stretch of the study area, two active earth slides / earth flows are present. The largest is the S. Leonardo landslide, a complex movement made up of a rotational slide-earth flow affecting the S. Cassiano and Wengen formations. The landslide was dated at about 5600 cal BP and shows clear evidence of activity. A smaller, but rather active movement, is made up by the elongated Col da Oi earth flow which has been dated at about 3150 cal BP. The landslide has recently disrupted the bridge along the road leading to Costa (fig. 15).

FIG. 15 - The Col da Oi landslide which affected a bridge on the road leading to the hamlet of Costa.

Debris-flow related landforms and processes

Debris-flow processes and related landforms are widely distributed at the base of the dolomite massifs, especially in the north-eastern part of the study area (e.g., San Cassiano valley) where they are responsible for the building of fans of various dimensions. Locally, debris flows have also affected and remodelled scree slopes and talus cones. Within the geomorphological map, they have been included among the gravitational landforms and processes, with the aim of emphasising the role of gravity in their onset and dynamics.

The source areas of debris flows can be mainly found within the outcrops of Dolomia Principale due to i) the high availability of debris produced by frost shattering; ii) the scarcity of vegetation on debris accumulation and iii) the presence of fractures conveying running water directly to the base of the dolomite cliffs.

The most relevant debris flow features can be found at the base of the Piz dles Conturines, Piz de Lavarela and Sas dla Crusc; minor ones are located along the western flank of the Monte de Lagazuoi, along the southern and south-eastern slope of the Gherdenacia, north of Colfosco, east of the Sassongher and on the northern slope of the Sella Group.

Currently, debris flows contribute to the modification of talus cones mainly by depositing debris within the channels incised by torrent erosion. Only in occasion of particularly intense precipitation, debris flows can produce accumulation lobes at the apex of cones and, less frequently, in the track and distal sectors.

This is the case of the two fans located in the vicinity of L'Armentarola and Cave Sarè (fig. 16), in the eastern sector of the study area. Both of them were mainly built due to debris flow processes, but present-day debris-flow deposition is normally limited to the apex of the fans and inside the main channel.

FIG. 16 - Fans mainly accumulated by debris flows located at the base of Piz dles Conturines. The fan in the centre hosts a quarry.

The debris-flow fans located at the base of the western slope of the Monte de Lagazuoi show different morphological features. They are almost completely covered by vegetation at the apex, but their channels and distal zones currently maintain a certain degree of activity proved by the presence of fresh and large accumulation to debris-flow lobes entering the forest, constantly prograding valleyward and, locally, almost reaching the road.

Worthy of note are some debris flows that occurred during Summer 2003 at the northern structural terrace of the Sella Group. The triggering cause was the rapid melting of debris-covered ice. Air temperatures, remarkably higher than the seasonal mean, favoured the melting process, allowing the initiation of hyperconcentrated fluxes. The depletion of debris from many spots on the structural terrace has allowed the identification of buried ice masses whose presence, at some 2000 m, is unusual in this part of the Dolomites (see section on periglacial landforms). This can be due to the peculiar combination of topographic setting and slope aspect to the north. As for the topographic setting, the conservation of ice has been favoured by the presence of a sub-planar surface - on which the ice could form and be preserved - limited backward by a steep cliff leaving the ice-covered debris in the shade.

Talus cones and scree slopes

Often coalescent, talus cones and scree slopes are common features in the study area. They are made up of angular clasts from sub-metre to centimetre grain size deposited at the base of the dolomite massifs. Scree slopes mainly occur at the base of rock cliffs showing a more or less regular longitudinal profile and similar degree of fracturing. On the contrary, talus cones are located at the base of saddles or of intensively fractured sectors of the dolomite cliffs. Debris is generally produced by freeze and thaw cycles whose action is favoured by the intense rock jointing and fracturing, often widened by chemical solution; the rocks which are most subject are those of Dolomia Principale, which is characterized by a thin stratification. The mean inclination of cones and scree slopes is usually between 20° and 30°, typical of debris deposits mainly formed by the sole gravitation force (Marchi & Tecca, 1996; Baroni & *alii*, 2007). Their longitudinal extent is rather limited if compared to that of cones remodelled by debris flows. The most active sectors of scree slopes and talus cones are the upper ones, which are almost free of vegetation.

The most spectacular coalescent talus cones can be found inside the glacial cirques and inside the small glacial valleys of the Gherdenacia, Sella and Setsas mountain groups (fig. 17). Other minor coalescent cones are located on the northern structural terrace of the Sella Group, along the eastern flank of the Monte de Lagazuoi (from Cima Scotoni to Forcela Lagazuoi) and at the base of the dolomite cliffs of Gherdenacia, Sas dla Crusc and Piz dles Conturines.

Talus

Talus can be found almost everywhere in the area. Interpreted as talus are all those forms that cannot be assigned either to a scree slope or to a talus cone, but whose genesis is anyhow related mainly to gravity. Other processes, such as sheet erosion, may act to modify and reshape those deposits. Most of talus can be found on slopes at the base of dolomite massifs. Thanks to peculiar topographic conditions, talus may reach significant thickness, such as within open rock fractures, within lateral spread depressions or on structural terraces. On the geomorphological map, talus less than one metre thick has been depicted placing its symbol on top of the bedrock colour. Most of talus has been assigned an inactive state since it is covered by vegetation or by a thick soil.

In particular, wide talus deposits have been recognised on the eastern flank of the Gherdenacia, from the villages of La Villa to Pedraces. Their remarkable spatial continuity led to consider that stretch of slope relatively stable, if compared with most of the slopes of the study area.

Fluvial and slope landforms due to running water

Fluvial landforms are quite scarce in the study area. However, alluvial deposits and river terraces can be found along almost all the valley floors.

FIG. 17 - Val di Mezdì, shaped in correspondence of a fault line, and characterized by a series of remarkable active talus cones.

The alluvial deposits of Corvara in Badia, showing a triangular shape, formed at the junction between the Rü de Pisciadù, Rü Tort and Rü de Dlijia torrents. The first one drains the homonymous valley while the other two drain the slopes up to Campolongo Pass. The plain is mainly made up of lacustrine sediments deposited after the damming of the valley by at least two landslide events (see next section). The sediments are currently incised by torrents and show edges of fluvial erosion scarps.

Another alluvial plain, also showing a triangular form, is located at the junction between Rü Sciarè and Rü de Col dai Furns, in Valparola. The deposit is largely composed by dolomite angular-shaped clasts, transported down valley by debris flows occurred on the right flank of the Rü Sciarè, by the latter redistributed forming an alluvial fan. River terraces can be found along the Rü Sciarè river bed, as the result of successive erosion events. The sediments deposited by the Rü de Col dai Fürns show finer grain sizes, being derived by the erosion of the silty-clayey terrains of the Wengen and S. Cassiano formations, outcropping in Valparola.

Colluvial deposits mainly form inside topographic depressions within silty-clayey terrains where running waters, together with their fine load, are conveyed. The broadest deposit is at Pra de Sciarè, adjacent to the alluvial fan of the Rü Sciarè; it has been formed by sheet erosion and surficial transport occurring on the slopes of the Bosch de Sciarè.

Lacustrine features and landforms

Ponds, bogs and marshes are very common in areas affected by earth slides and flows, in particular at counter-slopes formed by slow rotational movements. Bogs form also uphill frontal moraines. Clearly evident are those at Prà de Dlira, in Valparola, and at Vallone Püdres, on the Setsas.

Residual lacustrine deposits, linked to landslide damming valley events, are present. A typical example, is the extensive deposit at Corvara in Badia, near Pescosta, where mass movements detached from the eastern flank of the Gherdenacia (Col Maladët) dammed the valley of the Rü Tort at least twice, forming a lake (Corsini & *alii*, 2001; Borgatti & *alii*, 2006). The first damming event, related to the Col Maladët landslide (a rotational rock slide, see tab. 1), has been dated 12,200 cal BP. A second movement took place around 3800 cal BP. The lake that formed has an estimated extent of some 1.5 km^2 along the axis of the valley and it was fed by the Rü de Pisciadù and by the Rü Tort, both draining areas affected by active processes and landslides. The sedimentary sequence, analysed from the stratigraphy of a borehole drilled at the assumed valley dam, show lacustrine deposits with a thickness of 19.5 metres, followed upward by a 1.3 metre thick alluvial fan deposit (Corsini & *alii*, 2001; Borgatti & *alii*, 2006).

Karstic landforms

Although the karstic action is quite limited for dolomite rocks, some karstic landforms are visible on the Gherdenacia plateau (around Col de la Sonè and on the Crespeina plateau) and on the Sella Group (at Plan de Sass). Those forms are doline-like depressions. On the summit surface of the Setsas, the chemical-physical action of running water seems to have substantially contributed to the deepening and widening of the SE-NW trending fractures within the rocks of the Dolomia Cassiana formation.

Man-made landforms

The main landscape man-made modifications are related to tourist activities (especially ski-related ones). After the Second World War, the private initiative of some inhabitants of the valley converted what has always been a common transportation system on snow into a leisure activity, practiced on non-prepared slopes. At the same time, the economy of the valley - till then strictly linked to subsistence agriculture - was almost completely turned into tourist economy. The development of dwellings followed the ever-growing request of tourist services, virtuously stimulated by an increasingly diverse offer of ski-run types. Mass tourism has caused deep modifications also to the natural landscape: the urban sprawl has in fact undergone a rapid increase, with some speculative character, above all during the 1955-1975 period, when residential housing and an increasingly denser cable car network were built. However, the greatest changes have been socio-economic ones. In fact, the greatest part of the active population found a job directly or indirectly related to tourist offer or administration, with only a few handcraft, breeding and farming activities left alive. During the last years, a new equilibrium has tried to be reached, through the regulation of new planned houses and a more environment-friendly thinking.

The highest number of ski slopes is on the mountain flanks of Pralongià, Piz de Surega, Corvara in Badia and Piz la Ila, including the famous race track traditionally used for a competion within the Ski World Cup. Other ski facilities are located on the slopes of the Sella Group, Gherdenacia and Valparola. In general, the ski slopes have not caused evident modifications to the natural morphology, apart from peculiar topographic situations that requested considerable slope cuts or depression filling. More evident are modification that affected vegetation and, in particular, forests, leading to frequent clear cuts. Commonly, the presence of ski slopes, due to their constant maintenance, is a mitigation element with respect to potential mass movements affecting the superficial part of deposits.

Although ski slopes caused significant morphological modifications, it was decided not to depict them on the map, to prevent masking information on landforms and deposits related to the natural morphological evolution of the area. Anyhow, their importance has been highlighted in a specific frame included in the geomorphological map.

Two other man-made modifications can be identified: the dumping site for the Municipality of Corvara in Badia and the quarry near Rü Sciarè. Both of them are located on debris flow fans. The dumping site breaks the natural morphology of the debris deposit, creating in it a central depression, partly filled by waste. The quarry, located at the base of the debris-flow fan, on the right flank of the Rü Sciarè, has created a 50 m high artificial scarp inside the deposit. At the base of the cone, on a first order river terrace of the Rü Sciarè, a rock-quarrying and sieving area is located (fig. 16).

CONCLUSIONS

The research has enable a detailed description of the geomorphological characteristics of the Alta Badia valley to be carried out, which have also been mapped in the annexed «Geomorphological Map of the Alta Badia valley (Dolo-mites, Italy)», at 1:20,000 scale. All the spatial information contained in the map, together with ancillary data, have been stored in a geographical database, with the main aim of providing the possibility of further implementations and elaborations, also in perspective of land-use planning.

Landforms in the area are largely related to mass movements that have progressively remodelled the main valleys during the Holocene, partly masking the older traces of LGM and Lateglacial origin, represented by glacial erosional and depositional landforms.

The high number of radiocarbon datings from different types of deposits has allowed a reconstruction of the geomorphological evolution of the area with respect to the changes of climatic conditions that occurred since the Early Holocene, thus adding a paleoenvironmental significance to the research.

The detailed geomorphological framework achieved has a twofold significance. On the one hand, it represents a sound basis for further applied studies, such as geomorphological hazard and risk assessments; on the other hand, it contributes to enhance the geomorphological value of this sector of the Italian Dolomites, recently included in the Unesco World Heritage List.

Considering the high national and international tourist vocation of the area, the output of this study may represent also a knowledge instrument for tourism, which can be declined through geo-tourist maps, public conferences etc., able to promote the fruition of the area more conscious of environmental issues.

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