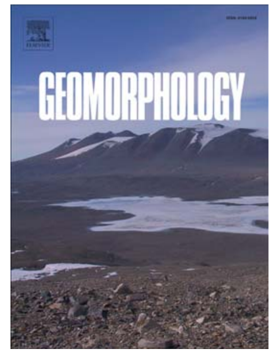


Evolution of a karst polje influenced by glaciation: The Gomance piedmont polje (northern Dinaric Alps)

Manja Žebre, Uroš Stepišnik, Renato R. Colucci, Emanuele Forte, Giovanni Monegato

PII: S0169-555X(16)30007-1
DOI: doi: 10.1016/j.geomorph.2016.01.005
Reference: GEOMOR 5486

To appear in: *Geomorphology*

Received date: 10 August 2015
Revised date: 9 January 2016
Accepted date: 12 January 2016

Evolution of a karst polje influenced by glaciation: the Gomance piedmont polje (northern Dinaric Alps)

Manja Žebre[1] , Uroš Stepišnik[2], Renato R. Colucci[3], Emanuele Forte[4], Giovanni Monegato[5]

[1]Geological Survey of Slovenia, Dimičeva ulica 14, 1000 Ljubljana, Slovenia; e-mail address: manja.zebre@geo-zs.si

[2]University of Ljubljana, Department of Geography, Aškerčeva 2, 1000 Ljubljana, Slovenia; e-mail address: uros.stepisnik@ff.uni-lj.si

[3]Department of Earth System Sciences and Environmental Technologies, ISMAR-CNR, Viale Romolo Gessi 2, 34123 Trieste, Italy; e-mail address: r.colucci@ts.ismar.cnr.it

[4]Department of Mathematics and Geosciences, University of Trieste, Via Weiss 1, 34128 Trieste, Italy; e-mail address: eforte@units.it

[5]C.N.R. - Institute of Geosciences and Earth Resources, Via Valperga Caluso 35, 10125 Turin, Italy; e-mail address: g.monegato@csg.to.cnr.it

Corresponding author: Manja Žebre

Abstract

Gomance is a piedmont karst polje in the northern Dinaric Alps presenting geomorphological and sedimentological evidence of past glaciation. During the Pleistocene the polje was situated at the edge of the Snežnik and Gorski Kotar ice fields from where two outlet glaciers reached Gomance. The morphogenesis of the polje was reconstructed by means of geomorphological mapping, sedimentological studies, and ground penetrating radar (GPR) measurements, supported by hand-drillings. With GPR an almost entirely buried moraine system was also imaged and mapped, crucial in reconstructing the polje history. The depression was karstified and well drained without any surface streams before the Last Glaciation. When the glacier front reached the depression, the entire floor became covered by glacial and outwash deposits. Surface runoff dominated over karst drainage in a large part of the polje, particularly where distal outwash deposits with low effective porosity functioned as an aquitard. These deposits diverted surface drainage toward the lowest edge of the polje, which functioned as a ponor front along the entire length. The outwash system of the Gomance polje was active during the Last Glaciation as suggested by radiocarbon-dated outwash deposits.

Keywords: polje; karst; glaciation; GPR; Dinaric Alps

1. Introduction

Karst is a landscape where a combination of high rock solubility and well-developed secondary porosity result in distinct hydrology and landforms (Ford and Williams, 2007). Dominance of chemical dissolution of karst rocks results in distinct surface and subsurface morphology. Chemical dissolution is a rather slow process, and consequently the dynamics of geomorphological processes in karst are in general slower than within other geomorphic systems. Dissolution is regularly the dominant process in karst environments, but it can be substantially altered by other geomorphological processes, such as intense mechanical weathering encompassed by mechanical erosion or intense slope processes (Ford and Williams, 2007). Characteristic forms associated with karst areas are a variety of karren, karst depressions, and conical hills as well as large levelled corrosion plains and intramontane basins (Mihevc, 2010). However, a combination of karst and other processes resulted in distinctive surface features and karst functioning. As a consequence, different types of karst environments formed: coastal type along the coasts, contact type alongside hydrological active contacts between carbonate and noncarbonate rocks, fluviokarst in the areas of high mechanical weathering of the surface and glaciokarst in high elevated plateaux affected by glaciations (e.g., Gunn, 2004; Ford and Williams, 2007).

Glaciokarst areas of the temperate zone are situated within higher altitudes, which regularly have the characteristics of plateaux or systems of glacial valleys (e.g., Herak, 1972; Kunaver, 1983; Smart, 1986; Mihevc, 2010; Adamson et al., 2014; Žebre and Stepišnik, 2015). Glaciations shaped the karst surface leaving abundant glacial erosional and depositional forms as well as a variety of closed depressions, which are a typical result of the combination between glacial and karst processes (Smart, 1986). Poljes are the largest enclosed depressions in karst terrains, with a flat floor in rock or in unconsolidated sediments, steeply rising marginal slope at least on one side, and karstic drainage (Gams, 1978). However, in many cases the entire glacial outwash deposits were accumulated in those extensive surface depressions located in the mountains or at their footslopes, forming fans or wide plains within the karst terrain. These types of depressions were studied by Gams (1978), who defined them as piedmont-type poljes according to the hydrological classification system. Many studies are concerned with piedmont-type poljes (e.g., Gams, 1963; Giraudi et al., 2011; Jiménez-Sánchez et al., 2013; Adamson et al., 2014; Stepišnik, 2014) even though they rarely term them so. Based on the study of Velo polje in the Julian Alps in Slovenia (4 in Fig. 1A), Gams (2003) stressed that a piedmont polje formation is limited exclusively to the areas where proglacial and glacial deposits have partially filled earlier karst depressions. During his studies he noticed that glacial and periglacial material filling those poljes were accompanied with peat and clayey laminated deposits (Gams, 1963). Those fine-grained deposits were interpreted as a result of a lake that inundated the depression in post-glacial time because of the extensive impermeable glacial and periglacial fill (Gams, 1963).The study of the Campo Felice in Italy (5 in Fig. 1A) (Giraudi et al., 2011) provides evidence of several glacial events affecting polje development. During glacial events, the polje was inundated while interglacial stages were characterised by lake recession. The Comeya polje in Picos de Europa in Spain (6 in Fig. 1A) hosts torrential and proglacial lacustrine deposits within the polje floor. The end of lacustrine deposition was followed by the onset of peat deposition, which was established to an age between 14.734 ± 326 and 9.109 ± 74 cal. BP (Jiménez-Sánchez et al., 2013). Recent studies of piedmont type poljes surrounding Orjen Mountain in Montenegro (1 in Fig. 1A) (Adamson et al., 2014) revealed that they were filled mainly with outwash deposits during Marine Isotope Stage (MIS) 12, when the largest glaciation covered the mountain with an ice cap and when glacial and fluvial systems were strongly coupled. At that time, very efficient surface meltwater and sediment transfer systems were established. In the following glaciations, the coupling between the glacial and fluvial systems became weaker, creating a much less efficient sediment delivery system and a domination of karst vertical drainage over surface runoff (Adamson et al., 2014). On the other hand, the study of Krasno polje at the footslopes of the Velebit Mountains in Croatia (2 in Fig. 1A) (Stepišnik,

2014) showed that the polje was filled with sediments from at least two different glacial periods. In fact the polje floor is filled not only with outwash deposits but also two parallel moraine ridges preserved on the surface, indicating that the polje floor was covered by a glacier at least twice. In addition, the presence of floodplain deposits was also reported from the lowest sections of the polje (Stepišnik, 2014). These findings indicate that piedmont poljes are of great importance for studying the glacial history of karst terrains. They act as sediment traps, preserving a record of glacial events. Our research is concerned with a piedmont-type karst polje with toponym Gomance, located between Snežnik and Gorski Kotar plateaux in the Dinaric karst (3 in Fig. 1A; Fig. 2). The latter is a typical example of a well-developed karst where chemical dissolution acts as the major geomorphological process. However, during the most extensive Quaternary glaciation the Snežnik and Gorski Kotar plateaux hosted ice fields, covering an area of at least 140 km^2 (Žebre and Stepišnik, 2015) (Fig. 2A). Several outlet glaciers, one of them also reaching the Gomance polje, were draining the two ice fields.

The Quaternary filling of Gomance was already mentioned in the early twentieth century (Krebs, 1924; Cumin, 1927; Melik, 1935) with different genetic interpretations. The most detailed research, not only in the Gomance area but also encompassing the entire Snežnik Mountain, was made by Šifrer (1959). He identified large lateral and terminal moraines in the Andrinova draga Valley and outwash fans covering the Gomance polje. The latter were ascribed to the presence of two glaciers related to the Last Glaciation: one flowing from the northeast and the other one from the east. He highlighted the presence of lacustrine deposits in the southwesternmost part of the polje. The same author claimed that up to 2-m-high terraces above the bottom of the polje covered by lacustrine deposits are the result of springtime high waters. He concluded that the outwash deposits are not so widespread in comparison to the large extent of palaeoglaciers, which he explained as owing to the vertical karst drainage below the glaciers. More than 40 years later, a scapula of Bos primigenius was found in the proximal outwash deposits on the Gomance polje in quarry q3 (Fig. 3B), 4 m below the surface. It yielded a radiocarbon age of 17.1 ± 0.4 ^{14}C ka BP (Marjanac et al., 2001), which is equivalent to a calendar age of 17.7–19.7 cal ka BP (Reimer et al., 2013).

Fig. 1. Study area together with the locations of the areas mentioned in the text (A) and geological map of the Gomance polje (B). 1 – Orjen, Montenegro; 2 – Velebit, Croatia; 3 – Snežnik and Gorski Kotar, Slovenia-Croatia; 4 – Julian Alps, Slovenia; 5 – Campo Felice, Apennines, Italy; 6 – Picos de Europa, Spain.

Geological map is based on data from the basic geological map *of* Yugoslavia in scale 1 : 100.000 (*Šikić et al., 1972*).

The present research discusses a glaciokarst environment where glacial and outwash systems influenced the development of the Gomance karst depressions. This article has four key aims: (i) to present sedimentological and geomorphological evidence for glaciation of Gomance and provide a context with the surrounding formerly glaciated area, (ii) to use ground penetrating radar (GPR) data in order to refine the interpretation of sedimentological data, (iii) to discuss the relationship between karst and glacial processes, and (iv) to reconstruct the glacial history of Gomance.

2. General overview of the study area

The Dinaric karst, the largest continuous carbonate karst area in Europe, is situated within the western Dinaric Alps (Lewin and Woodward, 2009). The study area corresponds to the northwesternmost part of the mountainous Dinaric karst, called Snežnik and Gorski Kotar high karst plateaux. The highest peak is Veliki Snežnik (1796 m asl) (Fig. 2).

Fig. 2. Extent of the largest recognized glaciation in the Snežnik and Gorski Kotar after Žebre and Stepišnik (2015) (A). Distribution of glacial deposits in the area of Snežnik and southwestern

Gorski Kotar after Žebre and Stepišnik (2015) (B). Gomance study area is marked with a red square. For colour interpretation, please refer to the web version of the article.

The Gomance polje (Fig. 2) is bounded to the northwest by Snežnik Mountain and to the southeast by Gorski Kotar. From a geotectonical point of view, the study area belongs to the carbonate-built Snežnik overthrust that is being pushed up and over the northeastern limb of the Brkini flysch syncline (Šikić and Pleničar, 1975). The main front of the thrust crosses the Gomance polje in the W-E direction, while a more complicated thrust structure continues toward the southwest. Upper Cretaceous thick-bedded limestone, Palaeogene limestone, and Eocene flysch build the area south of the main front of the thrust. The polje slopes north of the thrust fault are made up of Upper Jurassic and Lower Cretaceous limestone, dolostone, and carbonate breccias. The floor of the polje is completely filled by Quaternary deposits, which continue toward the northeast (Šikić et al., 1972; Šikić and Pleničar, 1975: Fig. 1B).

The morphology of the Gomance polje is shaped at the junction between the NE-SW fault along the Andrinova draga Valley and the E-W thrust front (Fig. 1B). The polje is ~2.2 km long and 1.4 km wide, covering a flat area of about 1.9 km^2. The lowest point of the polje floor lies at ~900 asl. The flat floor of the polje is surrounded by steep slopes to the northwest and southeast with peaks exceeding 1100 m asl. Conversely, the northeastern slope gradually ascends toward the Andrinova draga Valley and Trstenik depression. The lowest rim of the polje is to the southwest at 921 m asl. The relief below is marked by an ~250-m-high structural escarpment owing to the thrust fault zone, where the karst spring of the river Reka is located (Fig. 3B). The Reka River is the largest sinking river of the Classical Karst area in Slovenia with mean discharge of 8 m^3/s (Mihevc, 2010). Its river basin is situated on the Eocene flysch surrounded by a large karstic region, also including the area of the Snežnik plateau south of the highest peak.

In the Snežnik and Gorski Kotar plateaux large annual mean values of precipitation are observed (Isotta et al., 2014) because of the closeness to the cyclogenetic area of the northern

Adriatic and the Genova Bay, which gives abundant precipitation intensified by the orographic effect (Zaninović et al., 2008). The weather stations around Snežnik Mountain and in the Gorski Kotar area receive ~3000 mm of mean annual precipitation (Zaninović et al., 2008), meanwhile only estimations exist for the highest parts. At the Gomance station (937 m asl) the mean annual precipitation reached 2792 mm for the 1931–1960 period with a mean annual air temperature of 6.6°C (Pučnik, 1980).

3. Methods

An interdisciplinary approach, combining geomorphological mapping as well as GPR measurements supported by hand-drillings and sedimentological studies, was applied in the research area.

Glacigenic features on the Gomance polje and its vicinity were described and mapped in the field using 1 : 10.000 (The Surveying and Mapping Authority of the Republic of Slovenia, 1996) and 1 : 25.000 (National geodetic survey of the Republic of Croatia, 1996–2010) topographic maps. Field mapping was supported by analysis of a 1-m resolution digital elevation model (DEM), derived from LiDAR data with point density from 2 to 10 m^2, and the relative horizontal and vertical accuracies of 0.30 and 0.15 m, respectively (Geodetic Institute of Slovenia). This LiDAR data is available only for the northwest part of the study area (Slovenian side, also combining a 250-m belt from the border). Therefore, the basis for the final geomorphological map is a DEM with a cell size of 5 by 5 m (The Surveying and Mapping Authority of the Republic of Slovenia, 2006) that covers the entire study area and from which a shaded relief map and 10-m spaced contour lines were derived. The ESRI ArcGIS 10.3.1 was used for all stages of the map production.

Sediment facies analysis was performed and sketched using classifications proposed by Eyles et al. (1983), Miall (2006), and Bennett and Glasser (2009). Five abandoned gravel quarries were examined in detail, while smaller outcrops in road cuttings enabled describing other deposits outside the quarries. In the Gomance polje, downstream of the gravel quarries, seven hand-drillings (Fig. 3B) up to 3.1 m deep were made in order to describe the distal (southwesternmost) deposition and to calibrate the GPR interpretation. In the recovered cores, two samples from d1 and d3 drillings (Fig. 3B) at 160 and 200 cm below the topographic surface, respectively, were taken for grain size analysis in order to determine the possible presence of loess in the southwest sector of the polje. The drillings were performed on 30–31 October 2014 after a period of abundant rainfall. Interpretation of the provenance of deposits was supported by geological maps at a scale of 1:100.000 (Šikić et al., 1972; Savić and Dozet, 1984).

The GPR data were collected with two distinct goals: to determine whether diamicton extend or not below the fan and to investigate the Gomance polje sedimentation in places without outcrops. We acquired 10 GPR profiles (four of them are provided in this paper and their locations are shown in Fig. 3B) by using a ProEx Malå Geoscience system equipped with a 250-MHz shielded antenna pair, which allows an adequate tradeoff between resolution and penetration depth. All profiles have been acquired with the same parameters: 512 samples, vertical stacking equal to 16, a trace interval of 0.2 m and a trace length of 204 ns. We used a Thales Promark3 DGPS for trace positioning, while the GPR triggering was done by an electromechanical odometer.

We applied a standard processing flow (e.g., Jol, 2009) that includes drift removal (zero time correction), background removal, elevation (static) correction (taking into account only the main topographic variations), geometrical spreading correction and exponential recovery, bandpass filtering, two-dimensional migration (f-k Stolt algorithm), and depth conversion. For the last two steps we used a constant velocity value equal to 0.13 m/ns. This value is roughly representative of the study area and was estimated through diffraction hyperbola fitting; in any case, vertical and lateral velocity variations are surely present.

4. Results

4.1. Geomorphological and sedimentological setting

Almost the entire Gomance polje floor is flattened by deposits, slightly inclined toward the southwest where the depression ends with a more than 21-m-high bedrock ridge. The northeastern part of the polje is covered with two fans (Fig. 3) having an average slope angle of 2–3^{o} in the apical part. Two ridges rise from the plain in the proximal part of the fans. Ridge r1 is made of bedrock and partially covered by scattered boulders, while ridge r2 is ~2 m high and ~100 m long and consists of loose deposits (Fig. 3B). These are characterised by matrix-supported diamicton (Dmm); matrix is silty sand, while clasts are subrounded to subangular, reaching up to 1 m in diameter. Striated and faceted clasts are common (Fig. 6). Jurassic dark grey limestone clasts prevail; while light grey limestone, dark grey dolostone, and carbonate breccia clasts of Cretaceous and Jurassic age can also be found within the sediments. The same prevailing lithology of deposits can be found in several ridges in the U-shaped Andrinova draga valley in the northeastern continuation of the polje (Fig. 3). This suggests the same provenance of deposits, originating from the Snežnik area. Similar deposits are preserved in the eastern continuation of the polje toward the Trstenik depression (Fig. 3). They are made of a similar unconsolidated and matrix-supported diamicton (Dmm) but are distinguishable for the scarcity of dark grey limestone and the presence of red limestone clasts, which indicate a provenance from the Gorski Kotar area. According to the sedimentological and geomorphological characteristics, these deposits and related ridges (except from bedrock ridge r1) are interpreted as supraglacial meltout and flow till and moraine ridges, respectively. No such deposits were identified at lower altitudes southwest of the Gomance polje. However, they are widespread throughout Snežnik and northeastern Gorski Kotar plateaux especially at the elevation span between 900 and 1200 m (Fig. 2B). Within this glacially shaped area, several very deep karst depressions, having their floor filled with tills and/or other glacigenic deposits, are common (Žebre and Stepišnik, 2015).

Fig. 3. Panoramic view (A) and geomorphological map (B) of the Gomance polje, including locations of two moraine ridges (r1-r2), drilling sites (d1-d7), outcrops in gravel quarries (q1-q4), and GPR profiles (g1-g4). For colour interpretation, please refer to the web version of the article.

Sediment characteristics of the two fans were determined from wide outcrops within the gravel quarries (Figs. 4 and 5). These deposits mainly consist of clast-supported, weakly cemented, and subrounded gravels. The bedding of the gravels is horizontal (Gh) with interbedded lenses of cross-laminated sands or silty sands (St). No discontinuities suggesting that the interruption of the sedimentation can be seen in the vertical stack. In gravel quarry q1, beds exceeding 1 m of massive cobble-size gravel (Gm) are more common than in the other sites; matrix is coarse sand, whereas sand lenses are missing. This site shows a general fining upward trend toward horizontally bedded sandy gravel (Gh), that characterises also the westernmost part of the quarry (Fig. 4). These outcrop sites are located across the eastern fan, which was apparently deposited by meltwater coming from the Gorski Kotar area and its junction with the northeastern fan. Here the petrographic signature of sites q2, q3, and q4 matches with the deposits of ridges r1 and r2. In the q2 and q3 sites deposits have similar characteristics, displacing clear horizontal to trough-cross bedding (Gh-Gt) marked by up to 30-cm-thick sandy lenses (Fig. 5A). These display a planar to cross lamination (Sh-St-Sp) with silt fraction being more abundant. The latter prevail in the topmost part of the q4 site, suggesting an energy fading of the outwash at the end of the aggradation phase. According to geomorphological and sedimentological characteristics, this fan system originated from meltwater from the Snežnik area.

Fig. 4. Outwash sediments in gravel quarry q1. (A) Shows horizontally bedded gravels (Gh) with interbedded lenses of cross-laminated sands or silty sands (St). (B) and (C) (a detail of B) show beds of massive cobble-size gravel (Gm) with absence of sandy lenses.

Fig. 5. Horizontal to trough-cross bedded (Gh-Gt), weakly cemented deposits, with common sandy lenses in gravel quarry q3 (A), having a floor occasionally flooded (B).

Fig. 6. Example of striated and polished clasts outcropping in one of the moraines in the study area.

In the distal (southwest) portion of the polje, the sediment filling was investigated through hand-drillings (Fig. 7). The topmost 3 m from the surface is characterised by silty-sands (Fsm) interbedded with fine to medium sands (Sh-Sm) with small pebbles. Layers of massive clay and silty-clay (Fm) are in the lower part of the d1, d2, and d3 drillings. Grain size analysis of samples taken from the d1 and d3 drillings show similar characteristics: clay predominates with 52.50% (d1) and 63.98% (d3), sand represents from 5.20% (d1) to 2.92% (d3), while the rest is silt. The stratigraphic pattern shows a transition from sandy-dominated deposits in the medium fan in d4, d5, and d6 to more fine-grained in the distal portion (d2, d3, and d4). The coarser deposits in core d7 are related to the vicinity of the bedrock ridge and can be ascribed to a mixing of colluvial within the fluvioglacial fines. Thin weakly-pedogenized intervals occur only in the d5 drilling at ~1.4 m. They show a light brown (2.5Y) silty A horizon passing to a Ck horizon with small carbonate concretions at 1.6 m. The presence of groundwater was recorded in the d3–d6 drillings between 1.3 and 2 m depth. The absence of thin lamination in upper layers and the occurrence of coarse sand allows us to rule out a lacustrine environment. Poorly developed soils and the absence of peat layers seem to support the presence of a well-drained alluvial system. At the top of the westernmost drillings (d1 and d7), the abundance of angular pebbles in silty matrix indicates slope deposition from the western bedrock ridge likely occurred subsequently to the end of fluvioglacial aggradation.

Fig. 7. Stratigraphic logs of seven (d1-d7) drillings (see Fig. 3B for their location), including locations of samples taken for grain size analysis.

4.2. GPR analysis

Figure 8 shows an example of three different processed and interpreted GPR profiles conducted along different transects: across the ~2-m high moraine ridge rising and outcropping above the outwash (g1), in a suboutcropping situation (g2), and over a buried moraine (g3). The moraine signature is always characterised by higher attenuating materials compared to the surrounding sediments and strong internal diffractions (on unmigrated profiles) testifying to its high internal inhomogeneity. The maximum penetration depth for the EM waves is down to 7–8 m for the outwash fan, while it is <3 m within the moraine. This behaviour suggests that the glacial deposits contain a significant amount of conductive thin sediments, which produce higher EM attenuation. Fan sedimentary layers are quite continuous even if sometimes they show strong amplitude changes and lie in onlap on the moraine.

Fig. 8. Examples of interpreted GPR profile across the outcropping (g1), the suboutcropping (g2), and the buried (g3) moraine. The M indicates the moraine body, while the blue dotted line is its approximate limit. The yellow dotted lines mark some layers within the sediments, while the moraines are not stratified. X–Y serves as a reference in the photo and in the profile (g1) to highlight the SE slope of the surveyed moraine. For colour interpretation, please refer to the web version of the article.

A similar sedimentary layering was imaged at the beginning (northeast) of the 1.3-km-long profile (g4 in Fig. 3B) acquired along the main axis of the polje and shown in Fig. 9. The subhorizontal continuous reflectors are apparent down to 6–7 m below the topographic surface (Fig. 9A) and can be interpreted as low attenuating materials like coarse sands and gravels. Moving toward the south (Figs. 9B and 9C), the EM penetration depth progressively decreases, even if the sedimentary structures are quite similar to the previous ones. This behaviour suggests that the portion of fine material gradually increases. In fact, in the segment close to 1 km from the beginning of the profile (Fig. 9D), the penetration is not able to image any reflector since the EM attenuation, probably related to silty sediments, is too high. In the southwesternmost part of the profile there is a sector with dipping sediments (Fig. 9E), which terminates on the limestone outcropping in the last 12 m of the profile (Fig. 9F).

Fig. 9. GPR profile across the Gomance polje. (g4) NE-SW 1.3 km GPR profile with the topographic profile along its path and the location of the borehole superimposed; (A)-(F) details of g4. (A) The subhorizontal sediment layering is clear up to about 6 m below the topographic surface; (B) layering less clear, but still recognizable; (C) layering difficult to identify because of higher EM attenuation; (D) layering not interpretable owing to the extreme high EM attenuation; (E) dipping layers; (F) contact between layered sediments and limestone. Dotted lines mark the sediment layering trend (in yellow) and the top of the limestone (L, in blue). Reverberations (RIV) caused by ringing phenomena are also highlighted. See text for further interpretation details. For colour interpretation, please refer to the web version of the article.

5. Discussion

5.1. The evolution of the Gomance piedmont polje

Poljes are polygenic features that normally develop along regional tectonic structures (Ford and Williams, 2007), but their further evolution is controlled by a complex series of processes. Consequently, different types of karst poljes based on distinct classification systems have been recognized (Gams, 1963, 1978; Ford and Williams, 2007). The Gomance polje belongs to the piedmont-type polje, defined as those situated at the footslope of a mountain and filled by large quantities of alluvium during glacial or periglacial conditions (Gams, 1978, 2003). Although studies focusing on such a polje are quite common (e.g., Gams, 1963; Giraudi et al., 2011; Adamson et al., 2014; Stepišnik, 2014), they are hardly ever referred to as this. Nevertheless, research about piedmont poljes highlights the importance of studying not only karst but also glacigenic processes that played an important role in the evolution of karstic environments.

The initial Gomance depression formed along two main faults crossing the polje (Fig. 1B). The polje surface was modelled mainly by karst processes sometime prior to first glacial occupation, while in the following phases it was infilled and flattened with deposits. On the basis of our results, we can distinguish two clear sedimentary phases occurring during cold glacial periods (Fig. 10) when the polje development was influenced by the nearby presence of two outlet glaciers (Fig.2A). The first phase (Fig. 10A) was characterised by the occupation of the outlet glacier over the entire northeastern part of the polje floor, which is evidenced by the buried moraine (r2) (Fig. 7) and glacial boulders covering the hilly bedrock (r1) in the middle of the polje. This outlet glacier likely generated in the Snežnik Mountain as inferred from the lithology of till and also the orientation of moraine ridge r2. Moreover, this marks the largest recognised extent of the Snežnik ice field. We found no evidence for the Gorski Kotar glacier reaching the Gomance polje at that time. The rest of the polje floor in front of the glacier margin was influenced by the outwash system, whose deposits were probably subsequently buried. Nevertheless, we assume a very fine-grained sedimentation in the distal and in the proximal outwash plain. This is suggested from occasional water retention at the bottom of gravel quarry q3 as well as in drillings d3–d6 and from the GPR data outcomes. Other causes for ineffective subsurface drainage are also possible, like the presence of older lodgement till and/or lacustrine deposits; however, they were not evidenced in our study.

In the second phase (Fig. 10B), the front of the Snežnik outlet glacier withdrew at least 800 m upward from the position reached during the first phase. Several moraines at this location and farther upstream in the valley have characteristics of hummocky moraines and can be related to ice-front oscillations. Even in this phase, the outlet glacier flowing from the Gorski Kotar ice field likely remained confined to the karst depression east from Gomance and did not reach the polje. Two outwash fans covered the northeastern part of the polje, and according to their position and sediment characteristics, one belonged to the outwash system of the Snežnik and the other to the Gorski Kotar outlet glacier. At that time, outwash sedimentation from both outlet glaciers was so abundant that it almost entirely buried the older, first phase glacial deposits on the polje. The thickness of the deposition in the proximal part is at least 13 m, as suggested from the largest depth of the quarry; but the full vertical extent of outwash deposits is not known. Moreover, there is no evidence of major erosional discontinuities within the coarse-grained outwash deposits; nor was a hiatus detected in the stratigraphic succession of the quarries, which is likely to be marked by red clay colluviated from the sides of the basin in a flat karst environment. Therefore, the entire sequence visible in the quarries very likely falls in the second sedimentation phase. Horizontally bedded gravels are common for the proximal part of the outwash fans with sandy lenses becoming more common in the topmost parts of quarry outcrops as well as in the distal part of the fans, where even more fine-grained deposits prevail. It is very probable that in this phase in general more material was transferred from glacial to the outwash environment as older glacial deposits as well as paraglacial deposits were available for reworking and transportation. The burial of the older moraine (r2) (Fig. 8) also indicates the overfilling of the polje, which is related to the very confined accommodation space. This behaviour is also testified by the GPR data, which show gradual increasing attenuation owing to the subsurface materials moving from the northeast to the southwest, i.e., toward the distal part of the outwash system. In fact, such attenuation can be related to a gradual lateral decrease of the grain size of the sediments, at least in the first meters below the present topographic surface. The grain size analysis on the samples taken within drillings d1 and d3, both in the distal part of the polje, supports this; only the first layer with angular pebbles points to slope colluvial sedimentation. Local attenuation effects could nevertheless be caused by local perched aquifers, forming after major rainfall events.

Fig. 10. Two reconstructed glacial phases in Gomance: (A) a peak of the Last Glaciation; (B) a final phase of the Last Glaciation (violet: moraines). For colour interpretation, please refer to the web version of the article.

The two main development phases of the Gomance polje can be potentially placed in the dynamics of the glacier fronts, similar to those recognised in the nearby Alps (Monegato et al., 2007; Luetscher et al., 2015), even if a better chronology is needed for this comparison. The dated Bos primigenius scapula found in the outwash deposits of quarry P4 yielded 17.7–19.7 cal ka BP (Marjanac et al., 2001; Reimer et al., 2013). Because the dated material was found 4 m below the surface, this age points to the fading of the Last Glacial Maximum (Clark et al., 2009; Shakun and Carlson, 2010; Lambeck et al., 2014; Hughes and Gibbard, 2015) for the end of the outwash aggradation. No datings are available for the precise timeframe determination of the first phase, but according to glacigenic deposits from the first and second glacial advance, that show no clear distinction in weathering, the first phase likely represents an early advance of the Last Glacial Maximum. The lack of organic carbon findings in the distal outwash deposits suggests a continuous waterlogging of sediments that prevented the development of vegetation, despite the relative abundance of water that locally promoted the preservation of forestall environment in the northern Dinarides (Monegato et al., 2015). Deposits related to older glaciations were not detected and are not reported so far.

5.2. Outwash systems in karst poljes

Sedimentological, geomorphological, and GPR results from the study area allowed us to hypothesise about the functioning of outwash systems in karst poljes. We present here a model, which explains the changing role of karst drainage related to glacial processes on a single karst polje.

- In the initial phase, before the occurrence of first glacial or proglacial sedimentation, the tectonically induced depression was karstified and well drained without any surface streams (Fig. 11A). Well-developed vertical drainage from the Gomance depression was possible owing to the polje position ~250 m above the local piezometric level. The beginning of glacial and proglacial sedimentation in the polje floor only partially halted vertical drainage into the karst. In this phase, the vertical drainage still prevails over the surface drainage (Fig. 11B).
- In the peak of proglacial sedimentation, the entire floor of the polje became covered by gravel, sand, and silt deposits with low effective porosity, thus functioning as aquitard and diverting surface drainage toward the southwest where the lowest edge of the polje is situated (Fig. 11C).
- The following ice-front oscillations resulted in alternation of glacial and proglacial deposition in the central and northeast section of the polje, while distal deposition continued in the southwest section (Fig. 11D).The latter represents the distal portion of the polje, which consists of silty-clay deposits. The contact between the latter deposits and karstified bedrock is in the lowest part of the Gomance polje, which was likely functioning as an ~3-km-long ponor front. Sediment flux through meltwater caused a constant aggradation in the outflow part of the polje, forcing continuous upward shifting of the ponor front on the contact with karstified bedrock. Consequent infilling of ponor points and activation of alternative outflows at higher elevations prevented a major outflow

system from developing. Therefore, there is no steep slope at the edge of the polje, which would suggest the location of a former concentrated subsurface runoff in the form of a ponor steep-head or a relict blind valley. The outflow was evidently dispersed along the entire length of the ponor front.

- The absence of a clear lacustrine phase indicates well-established subsurface drainage at the edge of the floor. Lack of suffosion dolines in any part of the Gomance floor additionally suggests that recent karst drainage below the deposits is efficiently halted (Fig. 11E). Therefore, we can infer that seepage through the deposits in the polje is negligible.

Fig. 11. Sketch of sedimentary and drainage evolution of the Gomance piedmont polje. Different colour of outwash deposits mark individual sedimentation phase. The pre-Last Glaciation phases are not considered because of a lack of evidence. See the text for a description of each phase. For colour interpretation, please refer to the web version of the article.

Although this model is based on the investigation of a single karst polje, it can be applied for studying the morphogenesis of piedmont poljes elsewhere in karst areas. By comparing several other studies of piedmont poljes from the literature, varieties of the model presented here can be distinguished. We do not have any evidence of lake existence at Gomance, thus our model does not consider a clear lacustrine environment. These findings are in good agreement with those from the Krasno polje in the Velebit Mountains (Croatia) (Stepišnik, 2014), where fine-grained alluvial deposits are situated in the lowest part of the polje. Also a recent study by Adamson et al. (2014) revealed no evidence for a lacustrine environment in piedmont poljes surrounding Orjen Mountain (Montenegro). Nevertheless, peat and laminated silty-clay deposits below outwash gravel imply that the Velo polje in the Julian Alps (Slovenia) was inundated after glacial retreat and later filled by fluvial deposits (Gams, 1963). A similar situation was reported from the

Comeya polje in Picos de Europa (Spain) where the sedimentation of lacustrine facies in the polje followed the deglaciation of the massif (Farias et al., 1996; Jiménez-Sánchez et al., 2013). However, Comeya was not occupied by glaciers as it was Gomance; instead it was only fed by meltwaters from the surrounding glacier. On the contrary, in the Campo Felice in the Apennines (Italy) a lake formed at the time of the glaciers expansion (Giraudi et al., 2011). The same is assumed for the Štirovača depression in the Velebit Mountains (Croatia) (Bočić et al., 2012), although without sedimentary indications. On the contrary with dispersed outflow at Gomance, the Krasno polje (Stepišnik, 2014) focused outflow in a small area where, owing to morphology, a steep-head valley was formed.

Geomorphological evidence, which would imply sinking of any significant sediment-laden outwash streams, was not identified in the area of Snežnik and Gorski Kotor. Thus, the results of our research suggest that outwash streams have to deposit the majority of sediment prior to submerging. Otherwise, aggradation of deposits inside the ponor systems would completely terminate runoff as in the case from the Štirovača ice cave from the central Velebit (Bočić et al., 2012), where strong infilling of the conduits with clastic sediments halted runoff during the entire last glacial period. The system was later reactivated when inflow of material completely ceased (Bočić et al., 2012).

6. Conclusions

Gomance polje in the northern Dinaric Alps contains a sedimentological record of past glaciations and thus represents the key area for studying piedmont type poljes.The formation of the Gomance polje was strongly affected by the nearby presence of the Snežnik and Gorski Kotar ice fields. Evidence of two clear sedimentary phases in the area of the polje was found through sedimentological, geomorphological and geophysical methods, accompanied by previous radiocarbon dating. The first phase was characterised by the presence of the Snežnik outlet glacier over the entire northeastern part of the polje, while the rest of the polje was influenced by the outwash system of the Snežnik and Gorski Kotar outlet glaciers. In the second phase, the front of the Snežnik outlet glacier retreated for at least 800 m, while the outlet glacier from Gorski Kotar was still limited to the karst depression east of Gomance. At that time, the outwash sedimentation almost entirely buried the first phase glacial deposits on the polje, and only one moraine ridge remained partially uncovered by ~2 m. Both phases can be placed in the Last Glaciation as suggested by radiocarbon-dated outwash deposits.

This sedimentological characterization of the Gomance karst polje not only revealed the most recent glacial history of this site but also allowed us to hypothesise about the interlacing karst-glacial functioning of one piedmont polje. Different effective porosity of allochtonous deposits filling a polje can have an impact on a karst aquifer functioning, and thus interchanging subsurface/surface drainage. In Gomance, this reflected in the glacigenic infill of the polje functioning as an aquitard and diverting outwash surface drainage towards the lowest edge of the polje, where a ponor front along the contact with karstified bedrock was established. Lack of suffosion dolines in any part of the polje floor and occasional water retention suggest that the deposits within the polje are still functioning as aquitard. This study demonstrates that a morphogenesis of piedmont poljes distinguishes from other karst depressions. We suggest this term should be used consistently while referring to this type of karst depression.

The present research gave a good focus on the mophogenesis and hydrologic function of the piedmont type poljes. However, we did not come across any evidence for older glaciations, which should be the focus of future research by retrieving a sedimentary core from the depression in order to get a long sedimentary sequence and even possibilities to uncover dating material.

Acknowledgements

We express gratitude to P.D. Hughes for very helpful comments to an early version of the manuscript. We would especially like to thank the Editor, Richard A. Marston, for his time and effort dedicated to improving the quality of this paper, as well as Jesús Ruiz Fernández, David Loibl and other three anonymous referees for their constructive comments. We also acknowledge Stacey Adlard and Iain Rudkin for helping us with the English revision.

References

Adamson, K.R., Woodward, J.C., Hughes, P.D., 2014. Glaciers and rivers: Pleistocene uncoupling in a Mediterranean mountain karst. Quaternary Science Reviews 94, 28–43.

Bennett, M.R., Glasser, N.F., 2009. Glacial Geology: Ice Sheets and Landforms. Wiley-Blackwell, Chichester, 385 pp.

Bočić, N., Faivre, S., Kovačić, M., Horvatinčić, N., 2012. Cave development under the influence of Pleistocene glaciation in the Dinarides – an example from Štirovača Ice Cave (Velebit Mt., Croatia). Zeitschrift für Geomorphologie 56 (4), 409–433.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial Maximum. Science 325, 710–714.

Cumin, G., 1927. Il gruppo del Monte Nevoso (Venezia Giulia). Bollettino della Reale Società Geografica Italiana, 1−2. Reale Società Geografica Italiana, Roma.

Gunn, J. (Ed.), 2004. Encyclopedia of Caves and Karst Science. Fitzroy Dearborn, New York, 902 pp.

Eyles, N., Eyles, C.H., Miall, A.D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. Sedimentology 30, 393–410.

Farias, P., Monserrat, J., Martínez, J., 1996. Nuevos datos sobre la estratigrafía del relleno cuaternario de la depresión de Comeya (Picos de Europa, Asturias). Geogaceta 20 (5), 1116–1119.

Ford, D., Williams, P.D., 2007. Karst Hydrogeology and Geomorphology. Wiley, Chichester.

Gams, I., 1963. Velo polje in problemi pospešene korozije [Velo polje and problem of accelerated corrosion]. Geografski vestnik 35, 55–64.

Gams, I., 1978. The polje : the problem of definition: with special regard to the Dinaric karst. Zeitschrift für Geomorphologie 22, 170–181.

Gams, I., 2003. Kras v Sloveniji v prostoru in času. Založba ZRC, ZRC SAZU, Ljubljana.

Geodetic Institute of Slovenia. LiDAR. Retrieved from http://gis.arso.gov.si/evode/profile.aspx?id=atlas_voda_Lidar@Arso

Giraudi, C., Bodrato, G., Lucchi, M.R., Cipriani, N., Villa, I.M., Giaccio, B., Zuppi, G.M., 2011. Middle and late Pleistocene glaciations in the Campo Felice Basin (central Apennines, Italy). Quaternary Research 75, 219–230.

Herak, M., 1972. Karst of Yugoslavia, In: Herak, M., Stringfield, V.T. (Eds.), Karst: Important Karst regions of the northern hemisphere. Elsievier, Amsterdam and New York, pp. 25–83.

Hughes, P.D., Gibbard, P.L., 2015. A stratigraphical basis for the Last Glacial Maximum (LGM). Quaternary International 383, 174–195.

Isotta, F.A., Frei, C., Weilguni, V., Perčec Tadić, M., Lassègues, P., Rudolf, B., Pavan, V., Cacciamani, C., Antolini, G., Ratto, S.M., Munari, M., Micheletti, S., Bonati, V., Lussana, C., Ronchi, C., Panettieri, E., Marigo, G., Vertačnik, G., 2014. The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. International Journal of Climatology 34, 1657–1675.

Jiménez-Sánchez, M., Rodríguez-Rodríguez, L., García-Ruiz, J. M., Domínguez-Cuesta, M. J., Farias, P., Valero-Garcés, B., Moreno, A., Rico, M., Valcárcel, M., 2013. A review of glacial geomorphology and chronology in northern Spain: Timing and regional variability during the last glacial cycle. Geomorphology 196, 50–64.

Jol, H. M., 2009. Ground Penetrating Radar Theory and Applications. Elsevier, Amsterdam, 524 pp.

Krebs, N., 1924. Fragmente einer Landeskunde des Innerkrainer Karstes. In: Zbornik radova posvećen Jovanu Cvijiću. Državna štamparija Kraljevine Srba, Hrvata i Slovenaca, Beograd, pp. 47–72.

Kunaver, J., 1983. Geomorphology of the Kanin Mountains with special regard to the glaciokarst. Geografski zbornik 12 (1), 201–343.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proceedings of the National Academy of Sciences of the United States of America 111, 15296–15303.

Lewin, J., Woodward, J. C., 2009. Karst geomorphology and environmental change. In: Woodward, J. C. (Ed.), The Physical Geography of the Mediterranean. Oxford University Press, Oxford, pp. 287–317.

Luetscher, M., Boch, R., Sodemann, H., Spotl, C., Cheng, H., Edwards, R.L., Frisia, S., Hof, S., Muller, W., 2015. North Atlantic storm track changes during the Last Glacial Maximum recorded by Alpine speleothemes. Nature Communications 6, 6344.

Marjanac, Lj., Marjanac, T., Mogut, K., 2001. Dolina Gumance u doba pleistocena. Zbornik društva za povjesnicu Klana 6, 321–330.

Melik, A., 1935. Slovenija: geografski opis. 1, Splošni del. Slovenska matica, Ljubljana, 700 pp.

Miall, A.D., 2006. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology. Springer-Verlag Berlin and Heidelberg GmbH & Co. KG, Berlin, 582 pp.

Mihevc, A., 2010. Geomorphology, In: Mihevc, A., Prelovšek, M., Zupan Hajna, N. (Eds.), Introduction to Dinaric karst. IZRK ZRC SAZU, Postojna, pp. 30–43.

Monegato, G., Ravazzi, C., Donegana, M., Pini, R., Calderoni, G., Wick, L., 2007. Evidence of a two-fold glacial advance during the last glacial maximum in the Tagliamento end moraine system (eastern Alps). Quaternary Research 68, 284–302.

Monegato, G., Ravazzi, C., Culiberg, M., Pini, R., Bavec, M. Calderoni, G. Jež, J., Perego R., 2015. Sedimentary evolution and persistence of open forests between the south-eastern Alpine fringe and the Northern Dinarides during the Last Glacial Maximum. Palaeogeography, Palaeoclimatology, Palaeoecology 436, 23–40.

National geodetic survey of the Republic of Croatia, 1996–2010. Topographic map at 1:25 000 scale.

Pučnik, J., 1980. Velika knjiga o vremenu. Cankarjeva založba, Ljubljana, 366 pp.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southonm J.R., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and MARINE13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon 55, 1869–87.

Savić, D., Dozet, S., 1984. Osnovna geološka karta SFRJ 1:100.000, List Delnice. Savezni geološki zavod, Beograd.

Shakun, J.D., Carlson, A.E., 2010. A global perspective on Last Glacial Maximum to Holocene climate change. Quaternary Science Reviews 29, 1801–1816.

Smart, P.L., 1986. Origin and development of glacio-karst closed depressions in the Picos de Europa, Spain. Zeitschrift für Geomorphologie 30, 423–443.

Stepišnik, U., 2014. Geomorphological properties of the Krasno polje, Nortern Velebit, Croatia. Dela 41 (1), 101–115.

Šifrer, M., 1959. Obseg pleistocenske poledenitve na Notranjskem Snežniku. Geografski zbornik 5, 27−83.

Šikić, D., Pleničar, M., 1975. Osnovna geološka karta SFRJ 1:100.000, Tumač za list Ilirska Bistrica. Savezni geološki zavod, Beograd.

Šikić, D., Pleničar, M., Šparica, M., 1972. Osnovna geološka karta SFRJ 1:100.000, List Ilirska Bistrica. Savezni geološki zavod, Beograd.

The Surveying and Mapping Authority of the Republic of Slovenia, 1996. National topographic map at 1:25.000 scale.

The Surveying and Mapping Authority of the Republic of Slovenia, 2006. Digital elevation model 5m x 5m.

Zaninović, K., Gajić-Čapka, M., Perčec Tadić, M., Vučetić, M., Milković, J., Bajić, A., Cindrić, K., Cvitan, L., Katušin, Z., Dražen, Likso, T., Lončar, E., Željko, Mihajlović, D., Pandžić, K., Patarčić, M., Srnec, L., Vučetić, V., 2008. Klimatski atlas Hrvatske, Climate atlas of Croatia: 1961. - 1990. : 1971. - 2000. Državni hidrometeorološki zavod, Zagreb, 199 pp.

Žebre, M., Stepišnik, U., 2015. Glaciokarst landforms and processes of the southern Dinaric Alps. Earth Surface Processes and Landforms 40 (11), 1493–1505.

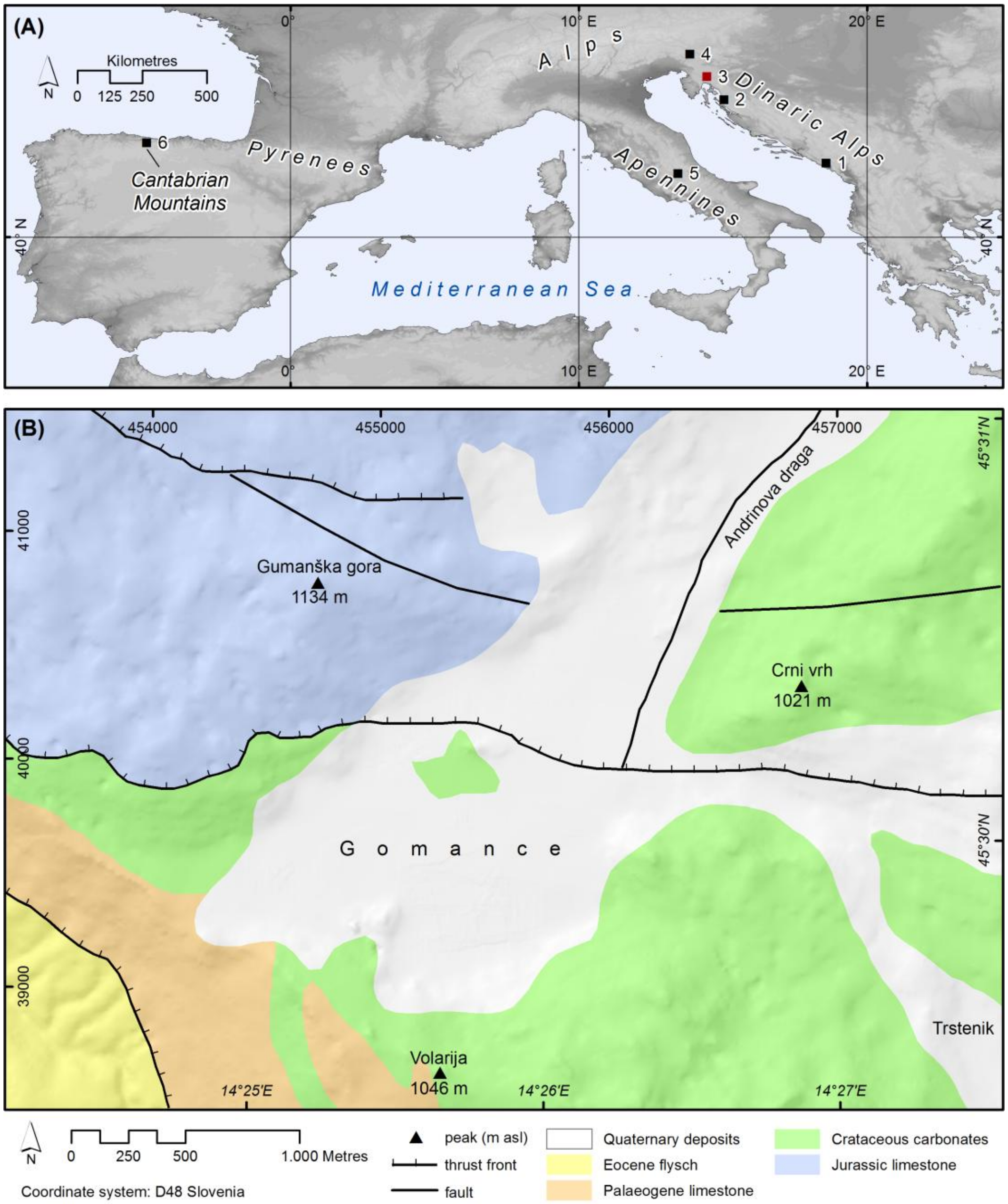
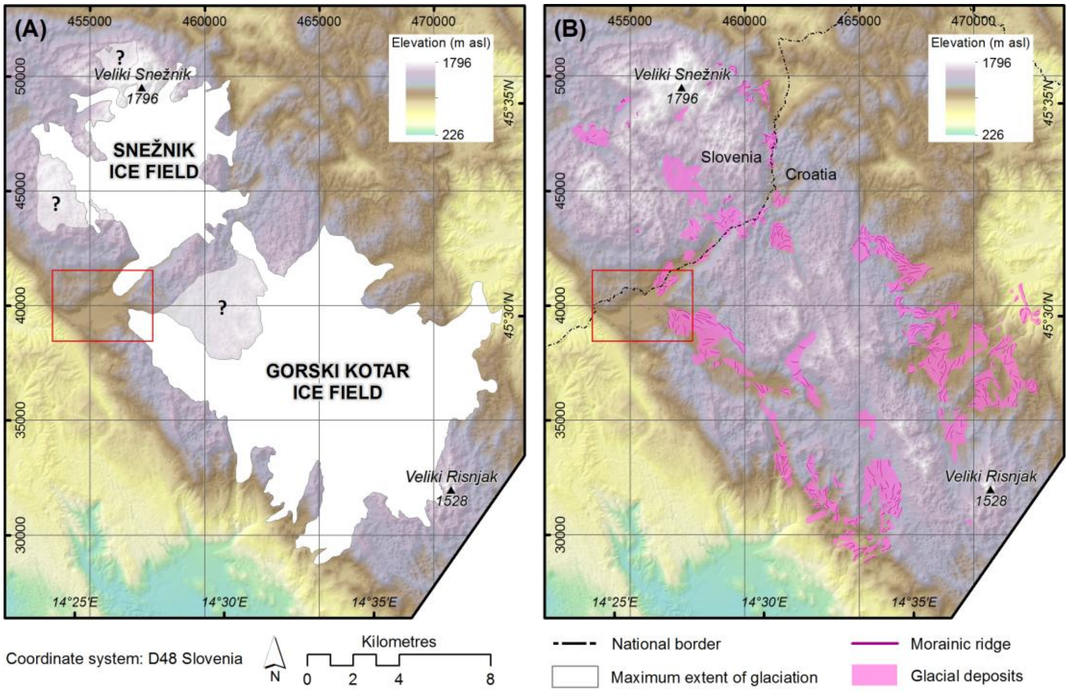

(A)
Kilometres
0 125 250 500
N
0°
10° E
20° E
40° N
A l p s
D i n a r i c A l p s
P y r e n e e s
A p e n n i n e s
Cantabrian Mountains
M e d i t e r r a n e a n S e a
1
2
3
4
5
6
(B)
454000
455000
456000
457000
41000
40000
39000
45°31'N
45°30'N
14°25'E
14°26'E
14°27'E
Gumanška gora
1134 m
Andrinova draga
Crni vrh
1021 m
G o m a n c e
Volarija
1046 m
Trstenik
N
0 250 500 1.000 Metres
Coordinate system: D48 Slovenia
peak (m asl)
thrust front
fault
Quaternary deposits
Eocene flysch
Palaeogene limestone
Crataceous carbonates
Jurassic limestone

Fig. 1



(A)
(B)
455000
460000
465000
470000
50000
45000
40000
35000
30000
Elevation (m asl)
1796
226
45°35'N
45°30'N
Veliki Snežnik
1796
?
SNEŽNIK
ICE FIELD
GORSKI KOTAR
ICE FIELD
Veliki Risnjak
1528
14°25'E
14°30'E
14°35'E
Slovenia
Croatia
Coordinate system: D48 Slovenia
N
Kilometres
0
2
4
8
National border
Maximum extent of glaciation
Morainic ridge
Glacial deposits

Fig. 2

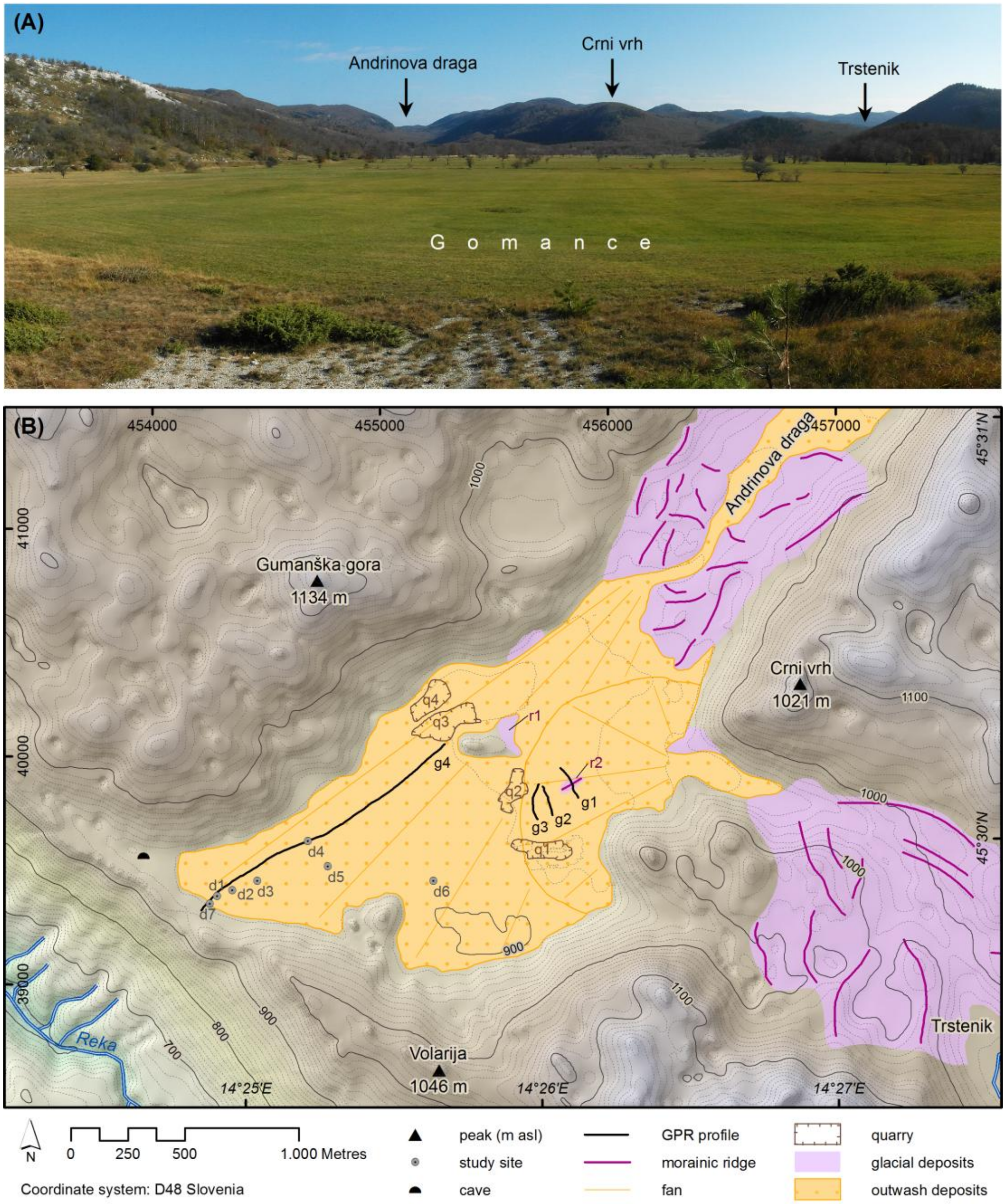
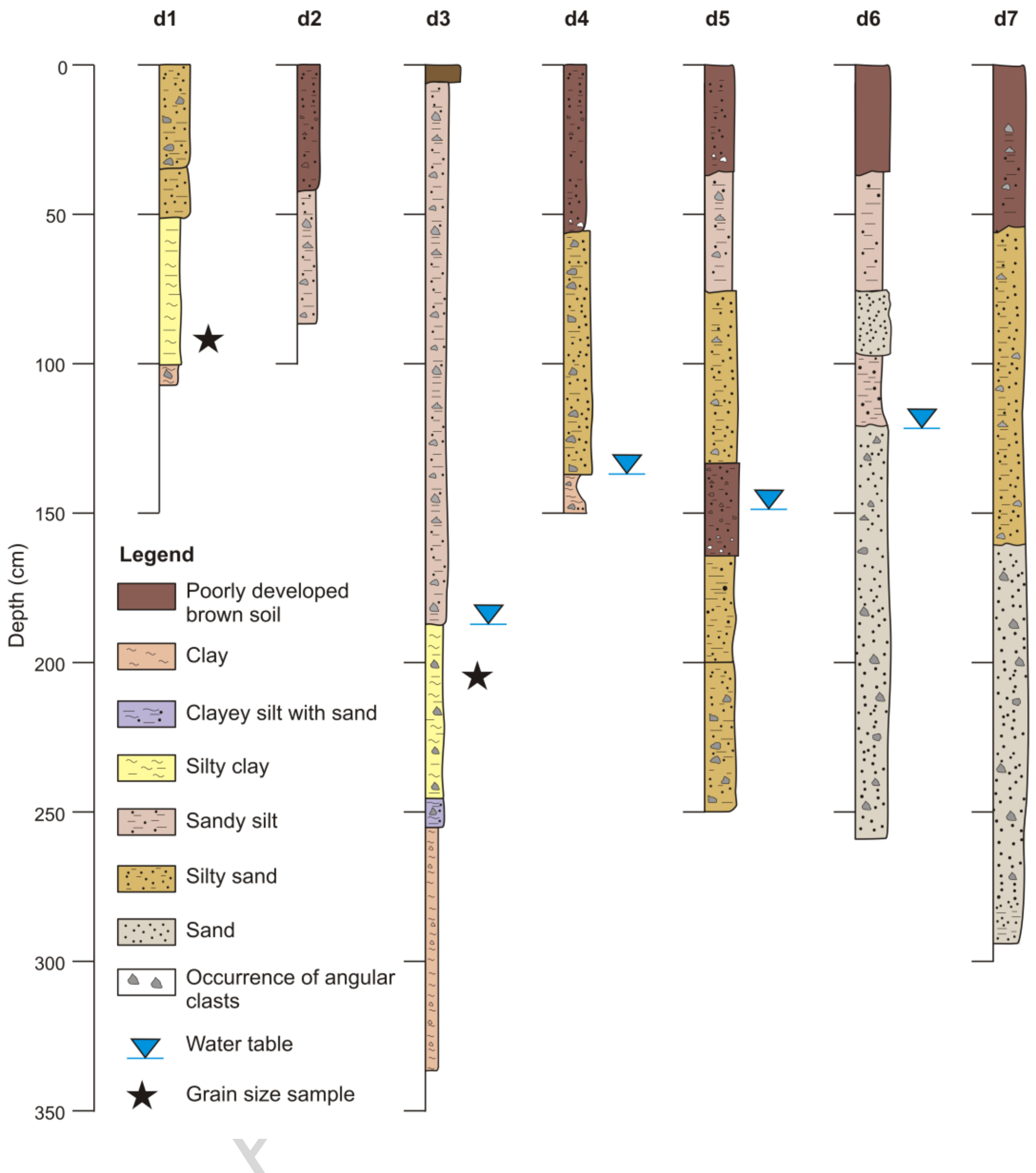

(A)
Andrinova draga
Crni vrh
Trstenik
G o m a n c e
(B)
454000
455000
456000
457000
45°31'N
45°30'N
41000
40000
39000
Andrinova draga
Gumanška gora
1134 m
Crni vrh
1021 m
Volarija
1046 m
Trstenik
Reka
14°25'E
14°26'E
14°27'E
q1 q2 q3 q4
r1 r2
g1 g2 g3 g4
d1 d2 d3 d4 d5 d6 d7
N
0 250 500 1.000 Metres
Coordinate system: D48 Slovenia
peak (m asl)
study site
cave
GPR profile
morainic ridge
fan
quarry
glacial deposits
outwash deposits

Fig. 3

Fig. 4

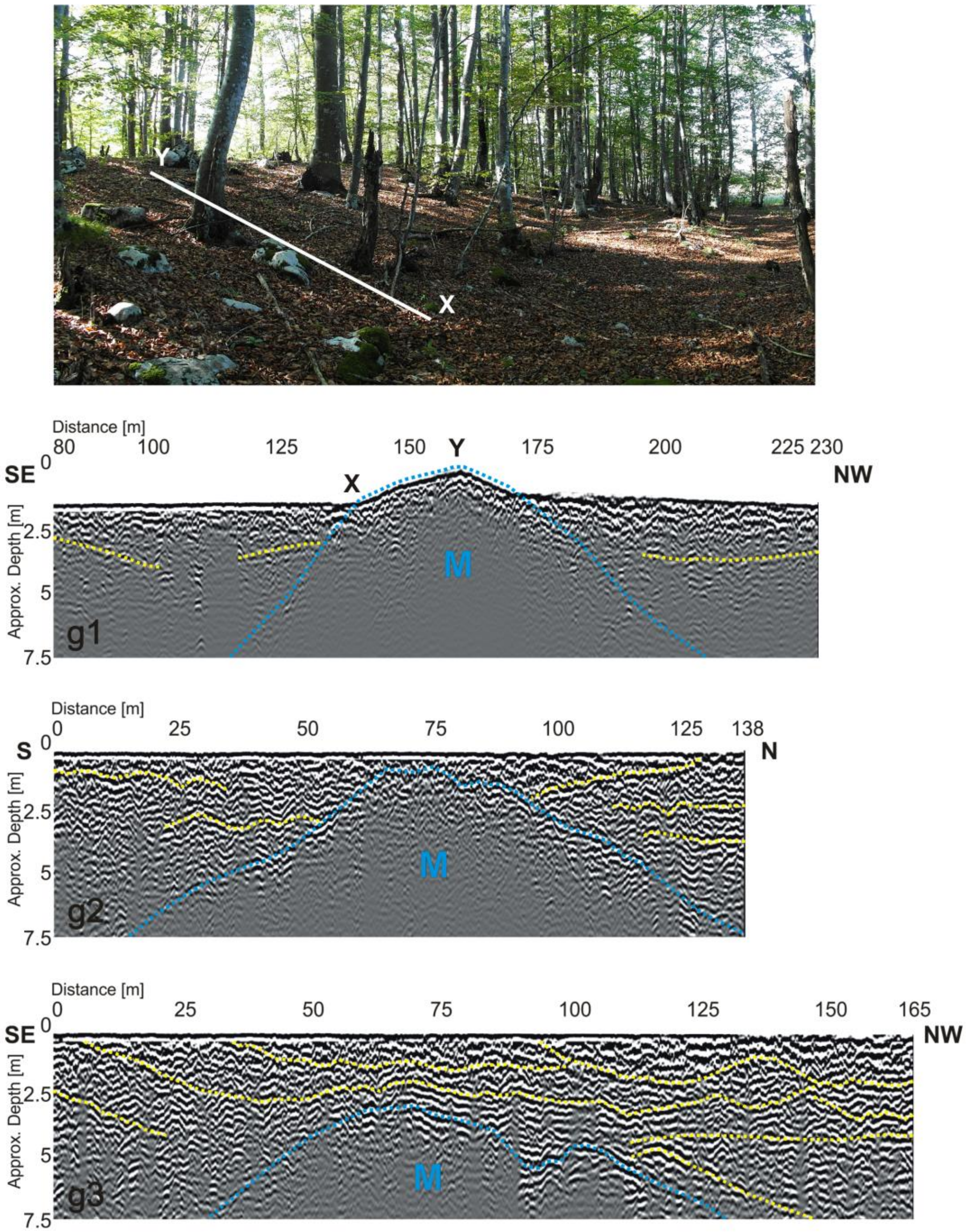
Fig. 5

Fig. 6



d1
d2
d3
d4
d5
d6
d7
0
50
100
150
200
250
300
350
Depth (cm)
Legend
Poorly developed brown soil
Clay
Clayey silt with sand
Silty clay
Sandy silt
Silty sand
Sand
Occurrence of angular clasts
Water table
Grain size sample

Fig. 7



Y
X
Distance [m]
80 100 125 150 175 200 225 230
SE
NW
Approx. Depth [m]
0
2.5
5
7.5
M
g1
Distance [m]
0 25 50 75 100 125 138
S
N
M
g2
Distance [m]
0 25 50 75 100 125 150 165
SE
NW
M
g3

Fig. 8

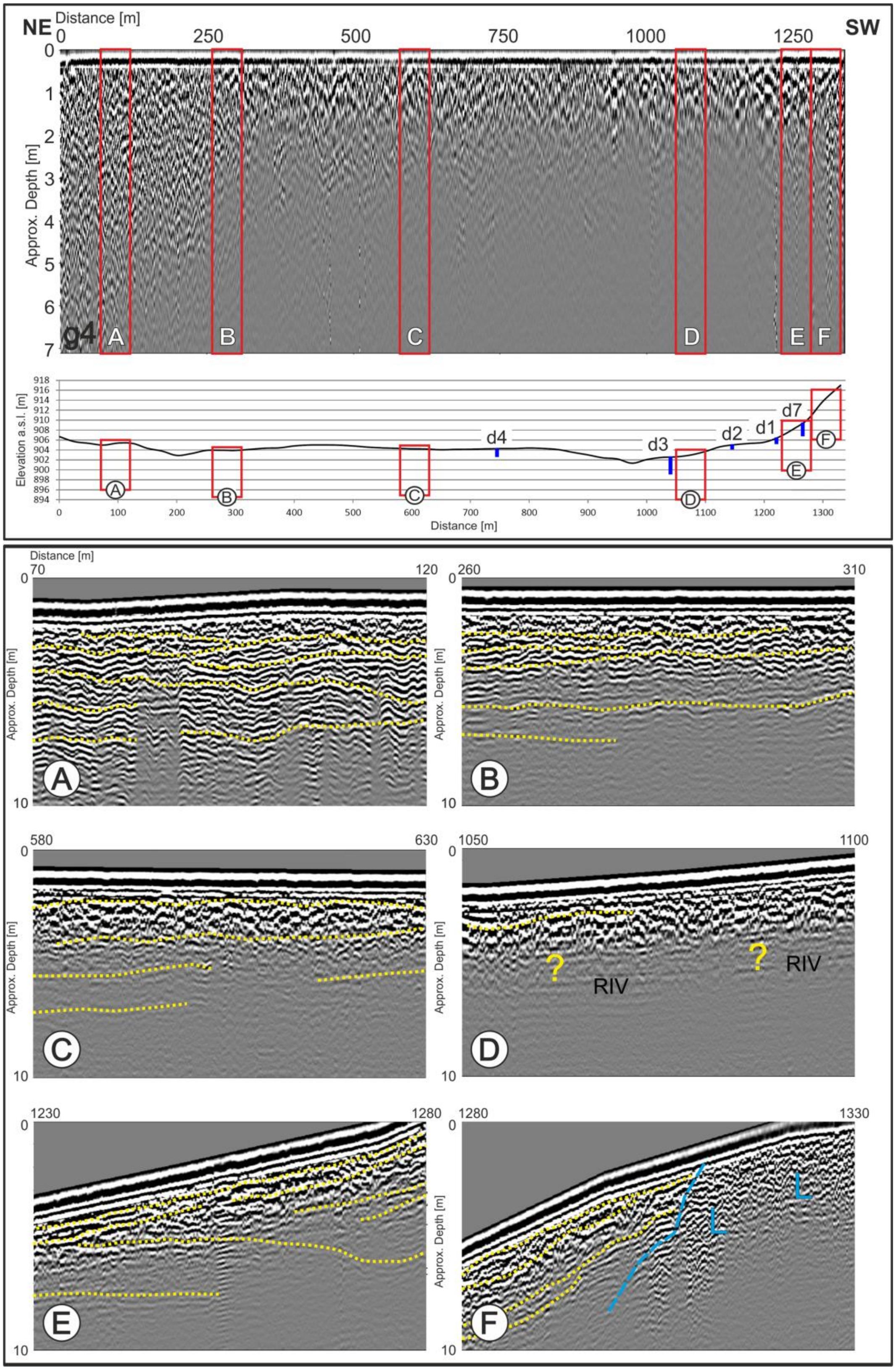
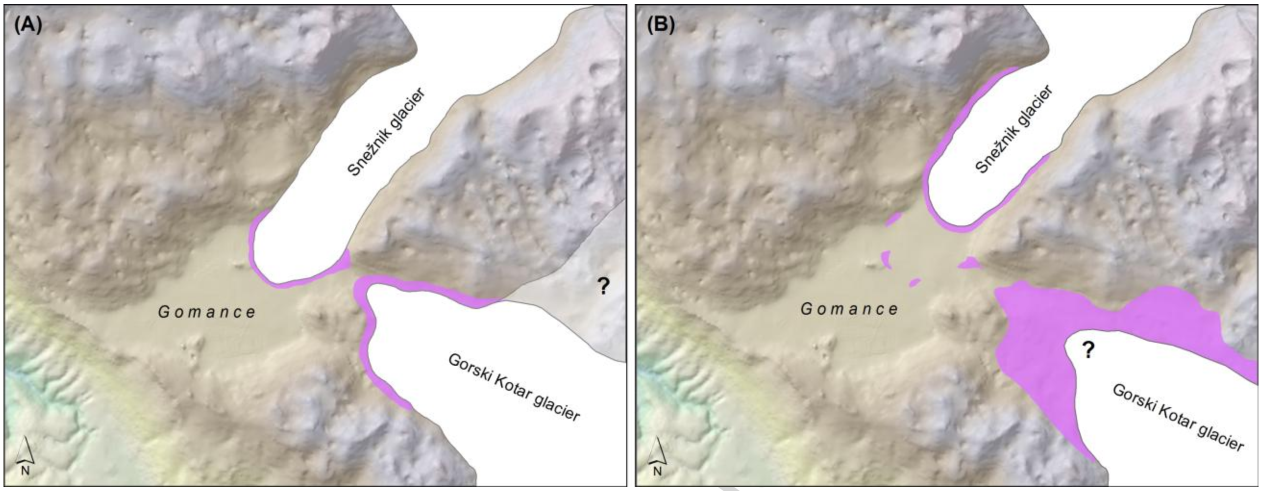
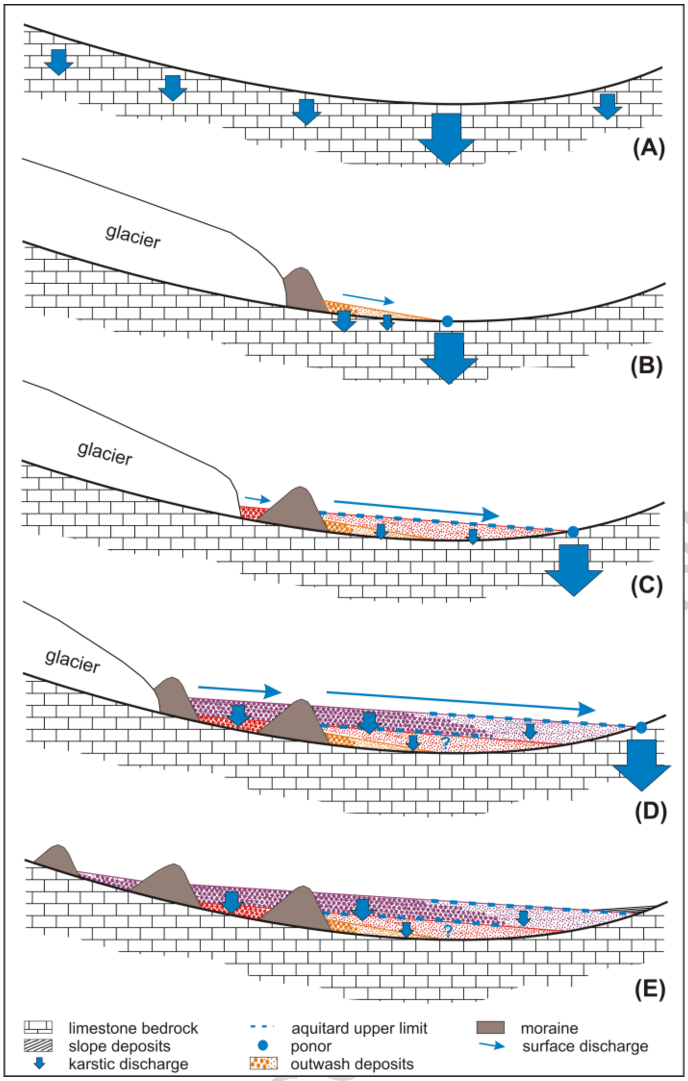

NE
SW
Distance [m]
0
250
500
750
1000
1250
Approx. Depth [m]
g4
A
B
C
D
E
F
Elevation a.s.l. [m]
d4
d3
d2
d1
d7
Distance [m]
RIV
RIV
?
?
L
L

Fig. 9



(A)
Snežnik glacier
Gomance
Gorski Kotar glacier
?
N
(B)
Snežnik glacier
Gomance
?
Gorski Kotar glacier
N

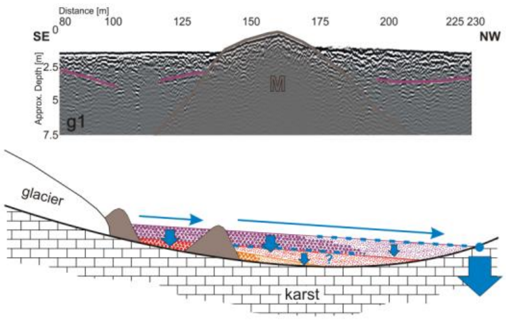
Fig. 10



(A)
glacier
(B)
glacier
(C)
glacier
?
(D)
?
(E)
limestone bedrock
slope deposits
karstic discharge
aquitard upper limit
ponor
outwash deposits
moraine
surface discharge

Fig. 11

Graphical abstract



Highlights (mandatory)

- Polje history reconstructed through geomorphology, sedimentology and GPR
- Karst polje evolution related to glaciation
- Glacigenic infill of the polje functioning as an aquitard
- Evidence of Pleistocene glaciation in the northern Dinaric Alps