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Karst geomorphology of carbonatic conglomerates in the Folded Molasse zone of the Northern Alps (Austria/Germany)

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ABSTRACT

The Folded Molasse zone of the Northern Alps consists of clastic sedimentary rocks that are usually not considered to be karstifiable. However, large areas within this zone are composed of carbonatic conglomerates. Numerous karst landforms have recently been discovered but are not recorded on official maps and in the literature. Therefore, a research programme was initiated at the Hochgrat site (Austria/Germany) that included geomorphological mapping and characterisation of the karst phenomena. Both fracture-controlled and hydrodynamically-controlled karren were observed on conglomerate outcrops. The predominant karst landforms, dolines, are typically circular, funnel shaped, most often 2 to 9 m in diameter, 1 to 6 m deep, and frequently act as swallow holes. Poljes that are atypically small (~1 ha) occur in either glacial cirques or syncline depressions, are flat floored and lined with sediment and soil, and drain underground via swallow holes. Short caves, springs with marked discharge variations and estavelles are further evidence for karst development. Karstic landforms are widespread in carbonatic conglomerate terrains, but their dimensions are smaller than in typical limestone karst. The practical implications of these findings are also briefly mentioned in this paper.

1. Introduction

Karstification typically occurs in biogenic, biochemical and chemical sedimentary rocks, mostly in carbonate rocks, such as limestone and dolomite (Johnson and Stieglitz, 1990; Groves and Meiman, 2005; De Waele et al., 2009), but also in sulphate rocks, such as gypsum and anhydrite (Black, 1997; Calaforra and Pulido-Bosch, 2003). Characteristic karst landforms include solutionally-enlarged factures and channels (karren), as well as closed depressions of differing origins, structure and dimensions (dolines, poljes). Cvijic (1893) described dolines as "the diagnostic karst landforms" (Ford, 2007). Karst aquifers are characterised by rapid, often turbulent groundwater flow in a network of fractures, conduits and caves (Goppert and Goldscheider, 2008; Plan et al., 2009; Worthington, 2009 Karst landforms usually indicate the presence of a karst aquifer, but a karst aquifer can also be present when such landforms are absent, for example in confined settings Huntoon, 2000); (Goldscheider et al., 2003. Karstification has many practical implications:

- Sinkholes in karst areas are geotechnical hazards for houses, streets and other infrastructure (Field, 2010; Vigna et al., 2010);
- Reservoirs and other hydraulic infrastructure in karst often exhibit leakage problems (Bonacci and Roje-Bonacci, 2008; Bonacci et al., 2009a);
- Karst areas exhibit significant biodiversity, at the surface, underground, and in groundwater-dependent ecosystems (Humphreys, 2006; Bonacci et al., 2009b);
- Karst aquifers are valuable freshwater resources but highly vulnerable to contamination; they consequently require special protection (Ravbar and Goldscheider, 2007);
- Deep karst aquifers are valuable geothermal resources (Goldscheider et al., 2010).

Therefore, the scientific investigation of karst landscapes and aquifers is important. The first step is to recognise karst areas as such. Areas consisting of clastic sedimentary rocks, such as sandstone, breccia and conglomerate, are usually not considered to be karstifiable.

Orogenic foreland basins (Molasse basins) generally include shallow marine to continental sediments documenting the uplift and erosion of the mountain range. Coarse-grained clastic sediments can be found near the orogenic belt and have often been deposited in large alluvial fans. Most mountain ranges include carbonate rocks. Carbonatic sand and gravel are therefore widespread in the sandstones and conglomerates in their foreland basins (DeCelles and Giles, 1996; Sinclair, 1997). As a result of late-orogenic tectonics and uplift, these formations are today often in an elevated position, exposed to weathering and groundwater recharge.

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Carbonatic conglomerates are predisposed to karstification, but only a few studies have reported karst development in these rocks, probably because karst researchers usually study limestone, while other geoscientists pay little attention to karst. Bergadà et al. (1997) have studied karst landforms and caves in carbonatic conglomerates of the southern foreland of the Pyrenees, Spain. Karstified conglomerates have also been reported north of the Pyrenees, in France (Bès, 1994). Scholz and Strohmenger (1999) mapped doline-like structures in conglomerate areas in the northern foreland of the Alps, Germany, which are not reported in any of the official geological maps or publications. South of the Alps, karst landforms and caves in conglomerates have been studied in Italy (Ferrarese and Sauro, 2005) and Slovenia (Gabrovšek, 2005). Gabrovšek also mentions the lack of knowledge concerning karstification of these rocks. Other than these scarce publications dealing with specific test sites, there is no systematic study describing the karst geomorphology of carbonatic conglomerates.

Therefore, a research programme was established in the conglomerate areas of the Molasse Basin near the northern margin of the Alps (Fig. 1). The study was done at two scales: detailed investigations at the most spectacular karst area within this zone, the Hochgrat Chain at the Austro-German border (rectangle in Fig. 1, map in Fig. 3); and regional-scale mapping accompanied by selected site investigations to obtain a more complete picture of karst phenomena in carbonatic conglomerates (main map in Fig. 1).

The study at the Hochgrat site included hydrogeological and geomorphological methods. Tracer tests from swallow holes to springs suggested flow velocities in excess of 100 m/h. High levels of faecal bacteria were found in spring waters, which can be attributed to the short transit times in the aquifer. These findings demonstrate that karstified conglomerates show similar hydrogeological characteristics typical of limestone karst aquifers, and the same spring water contamination problems (Goeppert and Goldscheider, 2011).

The geomorphological investigations included the mapping and detailed characterisation of karst landforms in the Hochgrat site and at selected other sites in the wider region, along with mineralogical and petrographical analyses. The goals of this study were:

- Make an inventory of karst landforms at different scales in carbonatic conglomerates, characterise their shape and dimensions, and compare and contrast them with corresponding landforms in classical limestone karst areas;
- Analyse the geomorphological and hydrological processes that created these landforms, again in comparison with typical limestone karst terrains;
- Highlight the consequences of these findings for groundwater source protection, geotechnical hazards, and other environmental and engineering aspects.

2. Geological setting

The Molasse Basin north of the Alps (Switzerland, Germany, Austria) formed during the Oligo-Miocene and includes a sequence of marine and freshwater sediments (Berge and Veal, 2005). The western and central part of the basin (from Geneva to Munich) was flooded twice by the sea and became fluviatile and continental

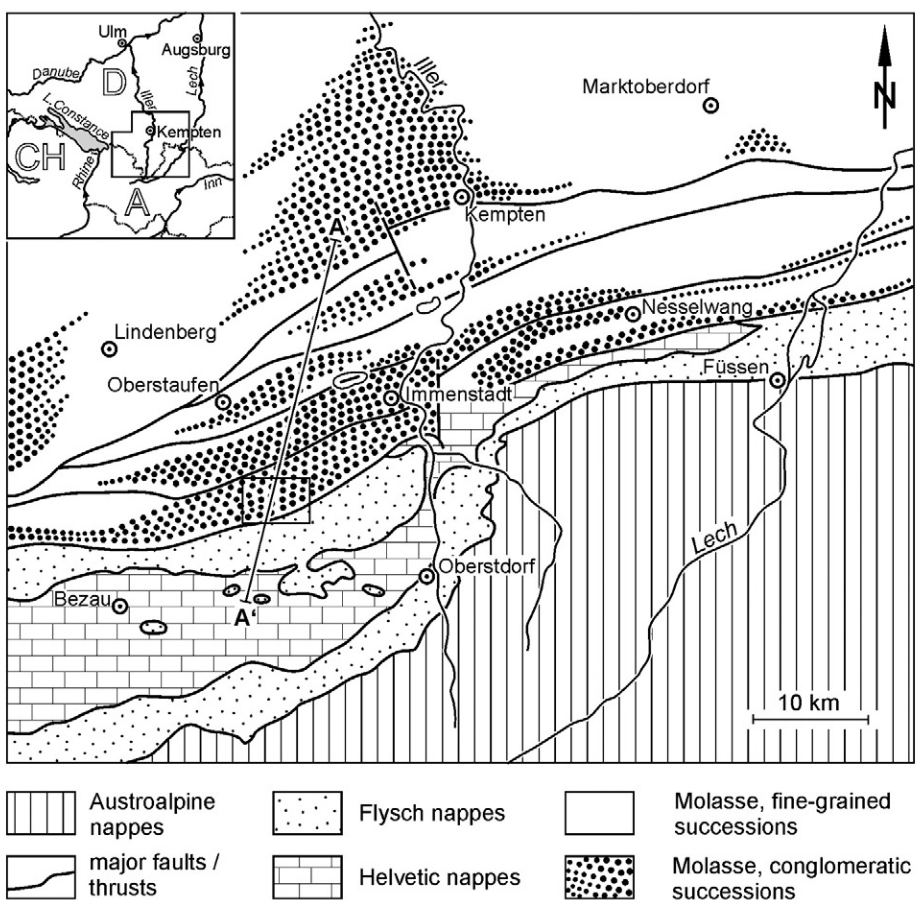

Fig. 1. Small map: Location of the wider study area at the northern margin of the Alps, in the border region of Germany (D), Austria (A) and Switzerland (CH). Large map: Geological map showing the distribution of conglomerates in the large Hochgrat-Adelegg Fan and parts of two smaller, adjacent fans. The location of the section in Fig. 2 (A-A′) and the map in Fig. 3 are also shown.
Modified after Scholz, 1995.

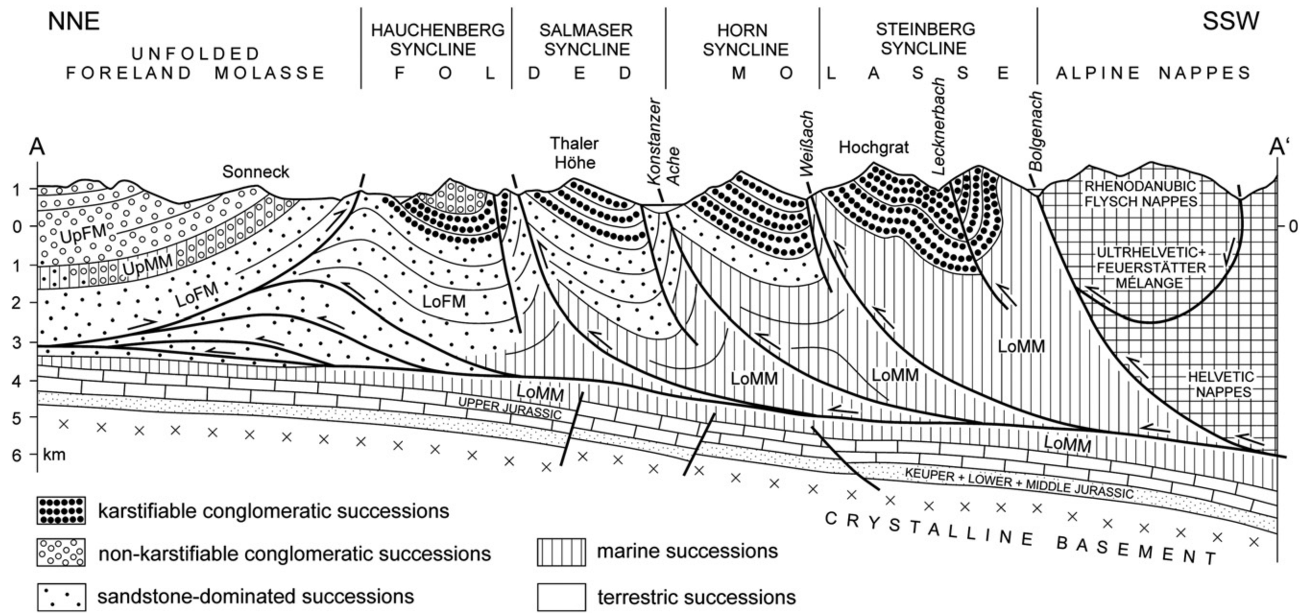

Fig. 2. North-South section of the Folded Molasse and the adjacent unit, the Unfolded Foreland Molasse in the north and the Alpine Nappes in the south. The stratigraphic sequence can be subdivided into Lower Marine and Freshwater Molasse (LoMM and LoFM, respectively) and Upper Marine and Freshwater Molasse (UpMM and UpFM, respectively). The Hochgrat test site consists of karstifiable conglomerates of the LoFM. Section line see Fig. 1.

between these transgressions and afterwards (Berger et al., 2005; Schulz et al., 2005). Therefore, the following stratigraphic sequence has been established for this part of the basin: Lower Marine and Freshwater Molasse, and Upper Marine and Freshwater Molasse (Scholz, 1995).

Sediment transport from the emerging Alps towards their foreland occurred via rivers that formed alluvial fans and deltas at the southern margin of the Molasse basin. Three large gravel fans including extremely coarse-grained conglomerates have been identified in western Austria and south-western Bavaria (Germany): the Pfänder Fan, the Hochgrat-Adelegg Fan, which originally covered more than 1000 km^2 (Fig. 1), and the Nesselburg-Auerberg Fan (Scholz, 2000). During the latest phase of Alpine orogenesis, the southern part of the basin was affected by compressive tectonics and, thus, became part of

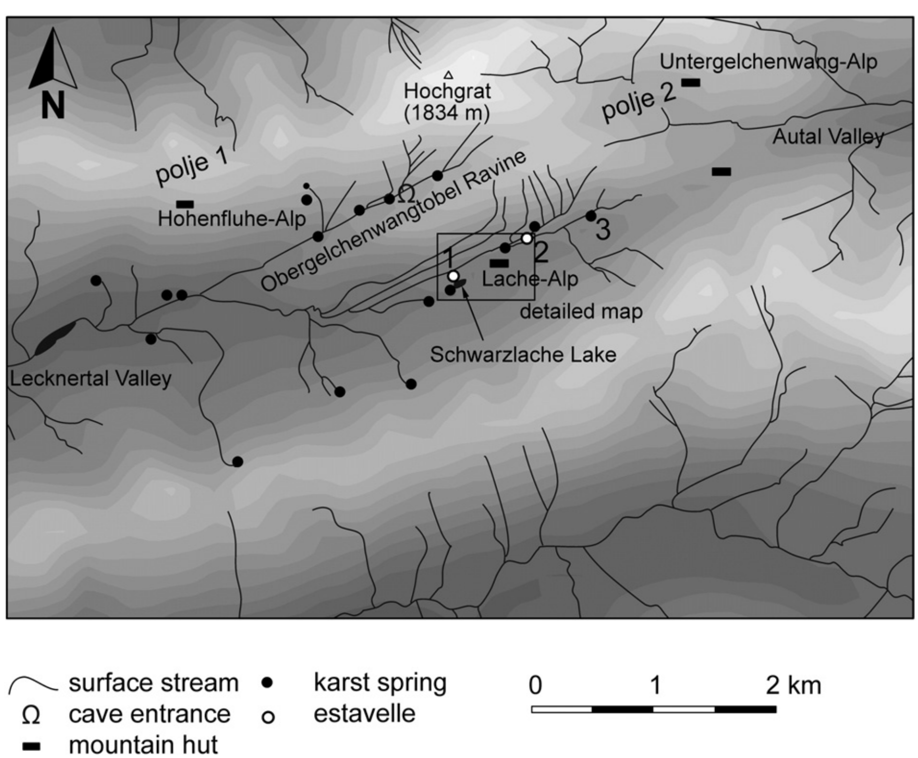

Fig. 3. Topographical and hydrological map of the Hochgrat test site (location see Fig. 1). The location of the detailed doline map, the polje in a glacial cirque (polje 1) and in a syncline depression (polje 2) and other relevant study sites are also shown (grey shades: altitudes, 50 m intervals).

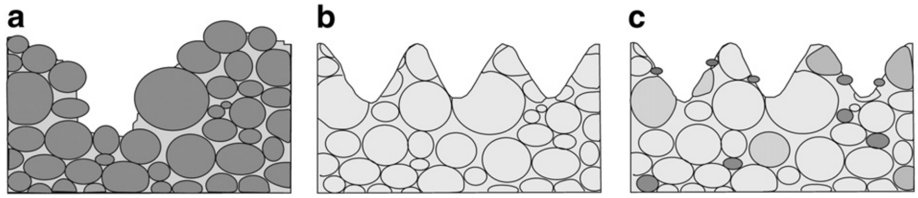

Fig. 4. Schematic illustration of weathering processes in conglomerates: a) mechanical weathering disintegrates the rock fabric and results in erosional channels; b) chemical dissolution of well-cemented carbonate conglomerates leads to the formation of karren and can be classified as true karstification; c) typical karren in the Hochgrat area, with non-soluble components that protrude during karstification.

the Alpine fold and thrust belt; this zone is called Folded Molasse (Fig. 2) (Scholz, 1995).

The Hochgrat (high ridge) test site is located at the border between the federal states of Vorarlberg (Austria) and Bavaria (Germany) and attains an altitude of 1834 m (Fig. 3). Structurally, it belongs to the so-called Steinberg Syncline, the southernmost thrust sheet of the Folded Molasse. The WSW-ENE-oriented Hochgrat Chain is separated from the parallel, southward adjacent chain by two aligned valleys that follow the axis of a regional syncline. The Lecknertal Valley drains towards the west, while the Autal Valley drains eastwards. The mountain pass between them is part of the continental water divide between the drainage basins of the Rhine (west) and Danube River (east).

The test site belongs to the Lower Freshwater Molasse (LoFM) and is located in the very centre of the Hochgrat-Adelegg Fan, to which it gave its name (Fig. 1). It consists of an alternation of coarse-grained conglomerate layers with a thickness up to 60 m and marl intercalations of usually less than 15 m. The conglomerates mostly consist of carbonatic components (limestone and dolomite pebbles) in a carbonatic matrix, but chert pebbles and other non-soluble grains occur as well. The pebbles are usually 5 to 10 cm in diameter but some attain 50 cm or more. The marls are of low permeability and low mechanical resistance, and are thus subject to erosion, while the conglomerates often crop out and form ridges and steps. The alternation of conglomerates and marls, the inclination of the strata and the glacial and post-glacial deepening of the valleys lead to slope instabilities. Several landslides, rock falls and other mass movements occurred in this zone (Seijmonsbergen et al., 2005).

3. Inventory and analysis of karst landforms

3.1. Karren

The Lexicon of Cave and Karst Terminology (Field, 2002) defines karren as “channels or furrows, caused by solution on massive bare limestone surfaces” and lists several types of karren. Although the Hochgrat site is not a limestone terrain, a wide range of channels and furrows can be observed. Channels on rock surfaces can form by mechanical erosion, chemical dissolution, or a combination of the two processes. Conventional weathering and erosion would primarily affect the matrix and cement, destabilise and disintegrate the rock fabric and eventually transform the solid conglomerate into loose gravel (Fig. 4a). Pure chemical dissolution of carbonatic conglomerates, i.e. true karstification, would affect both the components and the matrix or cement (Fig. 4b).

At the Hochgrat site, both processes can be observed, but most outcrops show clear dissolution phenomena that can be classified as karren. The conglomerates also include non-carbonatic components, such as chert and sandstone pebbles, which are resistant to dissolution and, thus, protrude during karstification (Fig. 4c). Hydrodynamically-controlled karren are frequent on inclined, poorly-fractured conglomerate outcrops. The channels are often ca. 10 cm wide, several metres long and separated by moderately rounded ridges (Fig. 5). Straight, parallel karren predominate on steep surfaces, while curved forms and herringbone patterns occur on gentler slopes. Fracture-controlled karren are less frequent but occur at places where the rock is intensely cut by fractures. Karren formation on surfaces of

Fig. 5. Typical karren on a conglomerate outcrop in the Hochgrat test site.

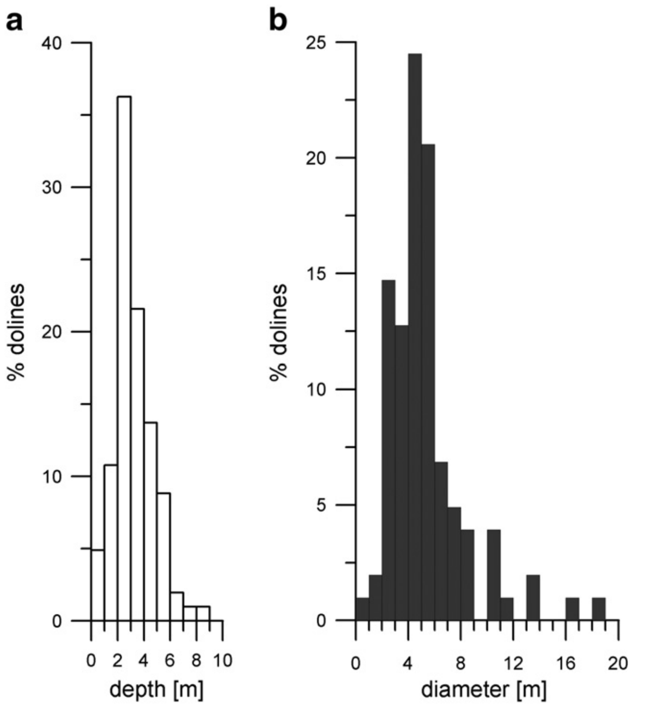

Fig. 6. Statistics of dolines near Lache-Alp (n = 102): a) depth; b) diameter of the analysed dolines.

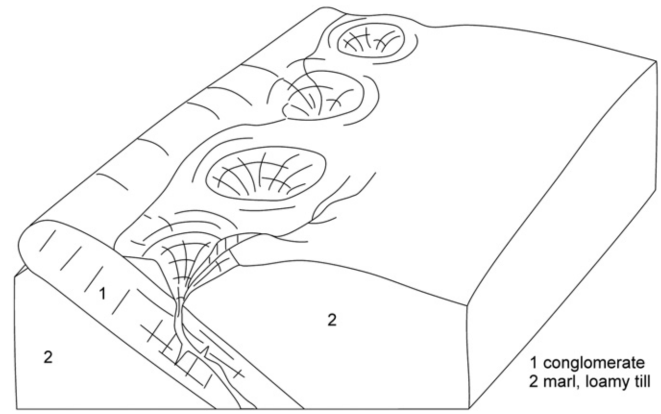

Fig. 8. Block diagram illustrating aligned dolines following the contact between conglomerate (1) and marl (2). The marl and loamy till generate surface runoff that sinks into the *underlying* karstified conglomerate layer via dolines that have open conduits or shafts at their bottoms.
Modified after Goeppert, 2008.

conglomerate blocks is also frequent, especially in the ´sturzstrom` at the entrance of the Lecknertal Valley, but also on erratic blocks deposited by glaciers in the Alpine foreland. In zones where the conglomerates are less well cemented and more affected by mechanical weathering, erosional channels can be observed on steep rock surfaces.

3.2. Dolines

A large number of small-scale dolines characterise the study area. Near the Lache-Alp hut in the upper Lecknertal valley, 102 dolines were mapped in an area of 40 ha (Figs. 6 and 7). The dolines are generally round and funnel-shaped; most dolines range between 2 and 9 m in diameter and are 1 to 6 m deep. Larger and deeper dolines also occur in the Hochgrat test site and other regions within the wider study area, but are much less frequent. Very small circular depressions only a few decimetres in diameter, presumably proto-dolines, were observed but not mapped and not included in the statistical analysis.

Dolines are often aligned along the strike of the strata and follow the contact between conglomerate layers and marl beds (Figs. 7 and 8). A part of the land surface is covered with loamy till. Both the marl and the till generate surface runoff that either joins the regional stream network (that follows thick marl beds) or sinks into nearby dolines. In the study area, 80% of all dolines have an active ponor at their bottom, sometimes in the form of an open but narrow shaft, which acts as a permanent or intermittent swallow hole for surface waters. This is a noteworthy difference to typical upland limestone karst areas where most dolines are dry (Ford and Williams, 2007).

The precise drainage modus of the ponor dolines depends on the dip of the strata and the topography. At most places, the surface

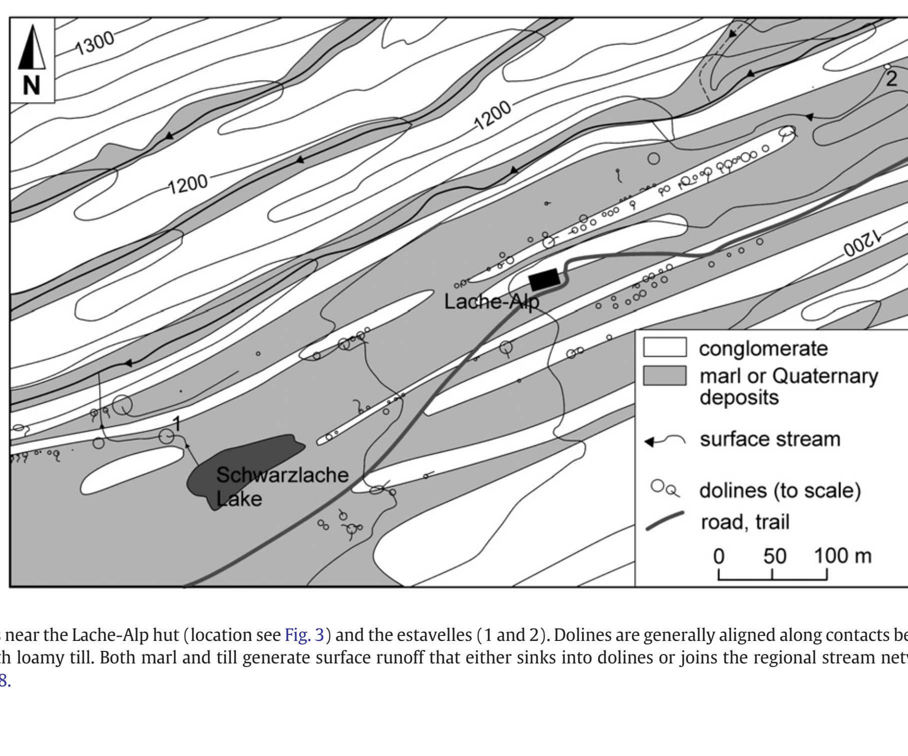

Fig. 7. Detailed map of dolines near the Lache-Alp hut (location see Fig. 3) and the estavelles (1 and 2). Dolines are generally aligned along contacts between karstified conglomerates and marls, partly covered with loamy till. Both marl and till generate surface runoff that either sinks into dolines or joins the regional stream network.
Modified after Goeppert, 2008.

streams that form on marl sink into the *underlying* conglomerate layer, as shown in the block diagram in Fig. 8. However, when both the dip of the strata and the slopes are steep, drainage sometimes occurs into the *overlying* conglomerate layer, as shown on the photo in Fig. 9.

3.3. Small-scale poljes

Poljes are closed depressions with a flat floor in karst terrains. The polje floor is often covered with soil and sediments. There is no external surface drainage but all surface waters, if present, sink into the aquifer via swallow holes, some of which transform into springs during high-water conditions (the latter are referred to as estavelles). Typical poljes in the Dinaric and other classical karst regions range between tens and many hundreds of square kilometres. Poljes are associated with a wide range of geological settings, such as tectonic grabens, pull-apart basins, broken anticlines or synclines (Ford and Williams, 2007).

In the study area, there are several small-scale depressions with flat floors covered with soil and sediments that drain underground via swallow holes into karstified conglomerates. In terms of geomorphological structure and hydrological behaviour, these depressions exhibit all the typical characteristics of poljes, but their size is only about 1 hectare. Gracia et al. (2003) present a short discussion on different size-criteria that have been proposed for poljes, such as 400 m or 1000 m as the minimum diameter of the polje floor. We argue that many geomorphological phenomena exist over a wide range of dimensions, such as all landforms associated with glaciers. Size is thus an inappropriate criterion. Therefore, we classify the described depressions in the Hochgrat area as small-scale (but real) poljes. These poljes are more than large dolines, because they are associated with more complex geological settings and not just funnel-shaped solution phenomena in karstifiable rocks. Although small in size, their dimensions are larger than the thickness of the individual conglomerate layers.

Two types of poljes have been identified. The first type occurs at high altitudes and developed from small glacial cirques (polje 1 in Fig. 3, Figs. 10a, 11). The depression is circular and ca. 100 m in diameter. The floor is covered with soil. Inflowing streams sink into the conglomerate karst aquifer via swallow holes. Paleo-swallow holes, ca. 2 m above the polje floor, indicate recent deepening of this polje by the combined action of carbonate dissolution and mechanical erosion of marl. Both the dissolved and suspended loads are drained via swallow holes.

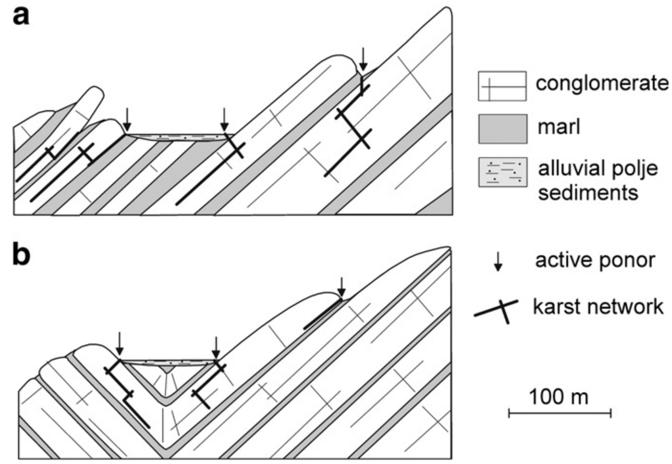

Fig. 10. Structural setting of small-scale poljes in the Hochgrat study area: a) polje that developed from a glacial cirque; b) polje that developed along the axis of a syncline (locations see Fig. 3).
Modified after Goeppert, 2008.

The second type is associated with fold structures and developed in the axial depression of a syncline (polje 2 in Fig. 3, Figs. 10b, 12). The polje is elongated along the fold axis; it is ca. 50 m wide, 250 m long, and its flat floor is covered with soil. Small intermittent streams from the bordering slopes sink underground via swallow holes at the margin of the polje floor.

3.4. Caves

Caves are characteristic underground phenomena of karst (Palmer, 1991), although they can also develop by other processes and in other geologic settings, such as lava tubes in volcanic areas (Calvari and Pinkerton, 1998). During this study and as a consequence of its preliminary findings, speleologists took notice of caves in the Hochgrat area. Today, six small caves have been explored but not yet surveyed in detail (A. Wolf, personal communication). The largest cave is a more than 100 m-long sub-horizontal water cave associated with a karst spring, located in a ravine SW of the Hochgrat summit

Fig. 9. Doline on the southern slope of the Hochgrat Chain at ca. 1600 m a.s.l., near the principal ridge. The dip of the strata is slightly steeper than the slope dip. Surface runoff from a marl zone (right) sinks into the *overlying* conglomerate layer (left) via a swallow hole at the bottom of this doline.

Fig. 11. Small-scale polje that developed in a glacial cirque. The recent depression drains underground via swallow holes.

(Obergelchenwangtobel Ravine, location see Fig. 3, impressions see Fig. 13a–c). Vertical cave shafts have also been discovered (Fig. 13d). The conduits often follow fractures and/or bedding planes, just as in typical limestone karst. The cross-sections of cave passages are often circular, sometimes oval or lemon-shaped, i.e. elongated along the fracture or bedding plane that controls the conduit development. Rectangular sections also occur, geometrically determined by bedding planes and fractures. At some places, speleothems have been discovered, such as the stalagmite in Fig. 13c. Similar to that shown for karren (Fig. 4), the combined action of mechanical erosion and chemical dissolution can be observed on the conduit walls, but chemical dissolution predominates. Therefore, the caves in this conglomerate area are classified as true karst caves. Several cave entrances act as springs; other caves are closely associated with nearby springs.

3.5. Swallow holes, estavelles and springs

From a hydrological point of view, karst areas are characterised by predominant underground drainage, indicated by a scarcely developed or entirely absent surface stream network, even under humid climatic conditions (Ford and Williams, 2007). In parts of the study area, there is a surface drainage network (Fig. 3), which seems to contradict the hypothesis concerning karstification of conglomerates. However, the streams mostly follow marl beds and partly flow over loamy till (Fig. 7), while large conglomerate outcrops drain underground, such as the dip slopes of the Hochgrat Chain (partly visible in Figs. 9, 10, 12). In the wider study area (Fig. 1), there are large areas without any surface drainage, despite the high precipitation in this region (1500–2000 mm/year). Swallow holes are frequent and often associated with dolines and poljes (Figs. 7–10). With few exceptions, swallow holes only occur in karst.

Estavelles, i.e. swallow holes that transform into springs during high-flow conditions, occur rarely and almost exclusively in karstic terrain. The largest estavelle in the Alps is located in the Hochifen-Gottesacker karst system, 20 km south of the Hochgrat. It is associated with a cave entrance at the side of the stream. When the estavelle acts as a swallow hole, up to approximately 500 l/s of stream water sink into the cave entrance. During high-flow conditions, the estavelle acts as a spring with a maximum discharge of approximately 4000 l/s

Fig. 12. Small-scale polje that developed along the axial depression of a syncline. The summits on the right side belong to the principal ridge of the Hochgrat Chain.

Fig. 13. Impressions from recently discovered but not yet surveyed small caves in the Hochgrat area: a–c) impressions from the water cave at the Obergelchenwangtobel Ravine; a) karst water near the cave entrance, b) typical cave sections, c) stalagmite; d) oval section in a vertical cave shaft (photos: R. Heinig).

(Goldscheider, 2005). Two smaller estavelles have also been discovered in the Hochgrat area. One is located ca. 350 m NE of the Lache-Alp (#2 in Figs. 3 and 7) and consists of an open fracture partly filled with boulders and gravel, ca. 1 m beside a stream bed. The block diagram in Fig. 14 illustrates the setting and functioning of this estavelle. It is situated at a geological contact and forms the hydraulic connection between a surface stream on marl and an underground conduit in a steeply inclined conglomerate layer. During extreme low-flow conditions, the stream bed is dry, while there might be underground flow in the karst conduit (Fig. 14a). During low to moderate flow conditions, the stream sinks completely or partially underground, with a maximum observed sink rate of 20 l/s (flow rates were measured using the salt-dilution method) (Fig. 14b,c). Under high-flow conditions, flow in the conduit exceeds its through-flow capacity, which causes the estavelle to transform into a spring capable of discharging flows of approximately 100 l/s (Fig. 14d).

Another estavelle associated with a doline was identified 400 m SW of Lache-Alp (#1 in Figs. 3 and 7). During low-flow conditions, the stream draining the nearby Schwarzlache Lake sinks underground into this doline. During high-flow conditions, the doline fills with water and eventually overflows. During extreme high-flow conditions, the discharge downstream from this doline is higher than the one upstream, thus confirming that the doline sometimes acts as a spring.

Springs discharging from conglomerates show the typical hydrological characteristics of karst springs, such as highly variable discharge in response to precipitation events and snowmelt. The spring orifices are sometimes covered with boulders or rock debris, but may also be associated with open fractures or cave-like conduits. During moderate-flow conditions, the discharge of these karst springs is approximately 10 l/s. In long, dry periods, some of the springs run dry. For example, storm events resulted in a discharge of 415 l/s at a karst spring near the Lache-Alp mountain hut (spring #3 in Fig. 3).

4. Discussion and conclusions

Carbonate conglomerates are widespread in the southern part of the Molasse Basin near the northern margin of the Alps. These clastic sedimentary rocks have been deposited in large alluvial fans during the Oligocene and Miocene, when rivers transported carbonate gravel from the emerging Alps northwards into their foreland basin. Subsequently, these formations were folded and thrusted and now form the Folded Molasse, a narrow mountainous strip between the main body of the Alps and their foreland.

Carbonate conglomerates of the Molasse Basin near the northern margin of the Alps are karstifiable, but few studies have actually investigated karst landforms in this area or other regions formed by carbonatic conglomerates. The Hochgrat Chain is a prominent mountain chain belonging to the Folded Molasse and arguably the area with the most spectacular karst development within this zone. Extensive and detailed fieldwork allowed the karst landforms in this area to be characterised, analysed and classified.

There is a wide range of surface geomorphological and hydrological karst landforms at different scales, such as karren, dolines, small poljes, swallow holes and estavelles. These phenomena indicate the presence of an underground karst drainage network, which can be directly accessed via small caves at some places. There are also transitions to landforms created by mechanical erosion and landforms due to mass movements, which are widespread in the Folded Molasse. However, in most cases, chemical dissolution, i.e. true karstification, is the predominant geomorphological process. Karst landforms in carbonatic conglomerates show many similarities but

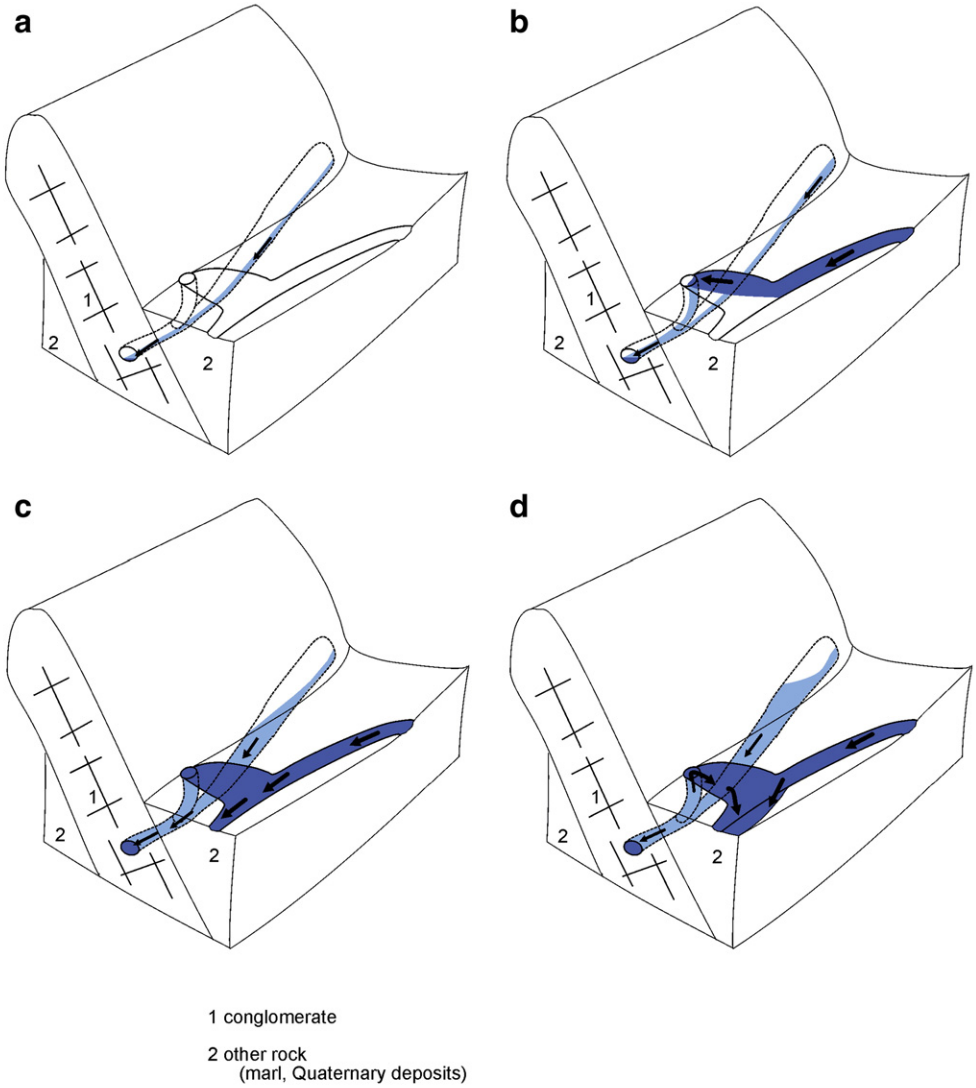

Fig. 14. Block diagram illustrating the geologic setting and hydraulic functioning of estavelle 2 near Lache-Alp (location see Fig. 7), during extreme low-flow to high-flow conditions: a) the streambed is dry; b) the estavelle acts as a swallow hole and the stream sinks completely underground; c) the stream sinks partly underground; d) the estavelle transforms into a karst spring.
Modified after Goeppert, 2008.

also salient differences to typical karst phenomena in limestone terrains, both in terms of genesis and morphology. However, due to the large variety of karst landforms and the lack of research on conglomerate karst, the following rules have to be considered as preliminary observations:

- Karren on conglomerate rock surfaces exhibit transitions between pure chemical carbonate rock dissolution and mechanical weathering.
- Dolines are widespread and relatively small but compared to typical limestone karst, conglomerate dolines are smaller, often 2 to 9 m in diameter, and they frequently act as swallow holes, while dolines in mountainous limestone karst regions are more often dry.
- Poljes in conglomerate karst are much smaller than their equivalents in limestone karst, typically only about 1 hectare, but they show all the diagnostic characteristics, i.e. closed depressions with a flat floor that drain underground via swallow holes. These depressions are more than just large dolines, as they are associated with more complex geological structures and/or have a more complex history. Two types of poljes have been identified: poljes that developed from a glacial cirque, and poljes in syncline depressions.
- Caves are mostly small, narrow and straightforward, but more speleological research is required before general regularities can be formulated.
- Outcrops of carbonate conglomerates mostly drain underground, while a network of surface streams is developed on marl intercalations and loamy till.
- A variety of karst hydrological phenomena were identified, such as swallow holes, springs with highly-variable discharge, and estavelles, all of which are typical hydrological expressions of an underground karst conduit system. However, compared to typical limestone karst aquifers, the dimensions of these phenomena are smaller.

Karstification has many practical implications, such as spring water contamination problems associated with rapid and turbulent flow in conduits (Pronk et al., 2007). Tracer tests in the Hochgrat study area have demonstrated very high underground flow velocities that often exceed 100 m/h. Seasonal spring water sampling for microbiological analyses have revealed that nearly all springs in the area show high levels of faecal bacteria, up to 65 *Escherichia coli* in a 100 ml sample (Goeppert and Goldscheider, 2011). These findings underline the practical relevance of karstification of these Molasse conglomerates for drinking water supply and protection.

In conclusion, carbonatic conglomerates in parts of the Folded Molasse and probably in other regions of the world are karstifiable. Similar to biochemical carbonate rocks, karstification starts when the carbonate content exceeds about 75%, as recently demonstrated by field and laboratory studies in the Hochgrat-Adelegg Fan (Flechtner, 2009) Karstified conglomerates show a wide range of geomorphological karst landforms, but also the same high vulnerability and water contamination problems as limestone karst aquifers. Therefore, the regional distribution and the specific characteristics of this type of karst landscape should be further investigated. Karstification of clastic sedimentary rocks of predominantly carbonatic composition has to be expected and should be considered for groundwater management and other practical issues.

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