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Karst genesis of the Swabian Alb, south Germany, since the Pliocene

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ABSTRACT:

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An integrated approach of geomorphological, speleological, climatological and stratigraphical analysis was applied in a selected study area in the Swabian Alb (south Germany) to determine the spatial and temporal development of deep karstification since the Pliocene. By correlating the field data derived from applying different analysis, four karstification levels could be identified and assigned to the regional landscape development. The oldest and highest level L IV represents only scattered relics of Late Tertiary karstification. Levels L II and L III are clearly determined by terraces and cave levels. They correspond to major stagnation phases of the regional base level of the river Danube and the pre-alpine glaciation in the Late and Middle Pleistocene. The lowest level L I evolved during the major glaciation of the Riss-period and is still active in the upper reaches but buried under younger deposits in the lower reaches of the area. The study points out the necessity of using different methods to characterise the evolution of karstification.

Key words: South-west Germany, Swabian Alb, Karst genesis, Karstification levels, Landscape evolution, Pliocene, Pleistocene.

INTRODUCTION

The Swabian Alb is the largest closed karst area of Germany, which has a length of more than 200 km from SW to NE and a width of 40 km (Text-fig. 1). As part of the SW German cuesta landscape it consists of a tilted plateau, composed of Late Jurassic limestones, whose karstification has long been studied (e.g. WAGNER 1941, STRAYLE 1970, VILLINGER 1972, DONGUS 1977). Most former workers distinguished between a period of shallow karstification, from the Cretaceous to the Miocene, and a period of deep karstification since the Late Tertiary (GLÖKLER 1979; VILLINGER 1986, 1987; LEMCKE 1987). The latter was caused by tilting and uplift of the plateau and the subsequent incision of rivers (e.g. WAGNER 1961; VILLINGER 1986, 1998; HÖTZL 1996). Until now, single genetic phases have not been determined and the impact of Quaternary climate changes on regional karst genesis is not very well understood.

The emphasis of this study is on the genesis of deep karstification since the Pliocene, which is responsible for the recent complexity of the karst hydrology. We followed a combined strategy to elucidate the karst genesis of the Swabian Alb by (i) using a simulation model developed by CLEMENS & *al.* (1997), BAUER & *al.* (1999), SAUTER & LIEDL (2000) and by (ii) analysing various field data to reconstruct former karstification levels. Here, we present the analysis of field data and their implications for the temporal and spatial evolution of the karst of the Swabian Alb. In contrast to the former workers who solely used geomorphological information, which can often result in ambiguous

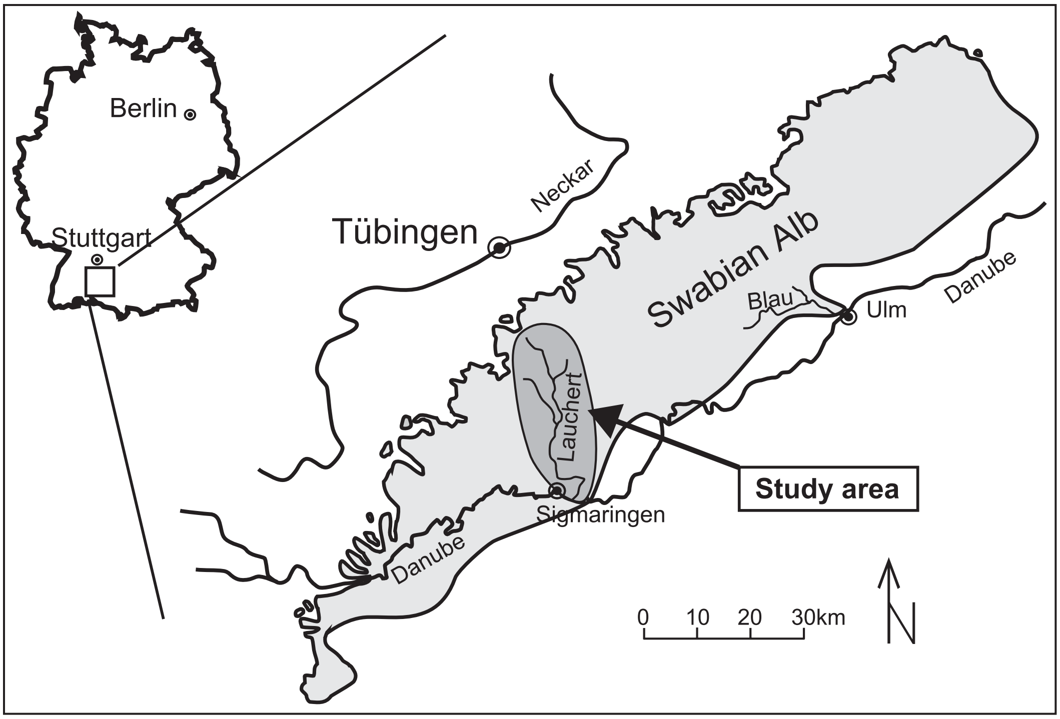

Fig. 1. Location of the study area

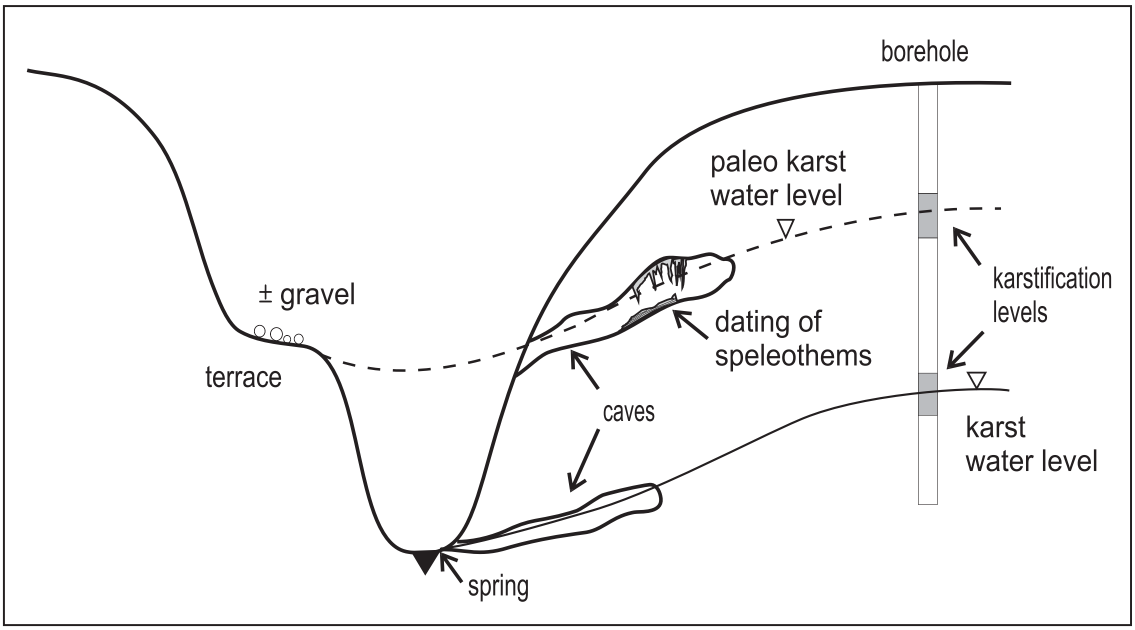

Fig. 2. Schematic sketch of the concept of correlation of surface levels and subsurface karstification levels

results as pointed out by GOUDIE (1994), we developed an integrated approach by combining geomorphological, speleological, climatological and stratigraphical data. In this paper we report on the first results by applying this concept to a selected area of the southwestern Swabian Alb.

CONCEPT OF CORRELATION OF KARSTIFICATION LEVELS

The concept of correlating surface and subsurface karstification levels (Text-fig. 2) is based on the assumption that carbonate solution preferably occurs at the water table level. Then, horizontal or slightly inclining cave passages can be used to reconstruct the former groundwater table and its relation to the regional fluvial base level (PALMER 1987). This is accepted by most researchers for low dipping and highly fractured carbonate rocks (e.g. FORD & EWERS 1978, FORD & WILLIAMS 1989). Phases of stagnation in the entrenchment of the rivers lead to a relatively static base level and to a likewise stable water-table within the regular range of fluctuations. After the rivers commence to erode their base level again, terraces remain at the surface as remnants of the former base-level and caves dry out due to the fall in water level. Text-fig. 2 presents a schematic sketch of the principle idea of combining information from terraces, longitudinal valley profiles, phreatic cave passages and karstified levels in boreholes, which we used in this study to distinguish between karstification levels.

This correlation of landsurface levels and subsurface karstification levels has already been successfully applied in various areas. In Kentucky, USA, MIOTKE & PALMER (1972), for example, compared levels of different cave passages in the Mammoth Cave System with the elevation of fluvial sediments and terraces of the major rivers in the surrounding area. They found that cavern development had been controlled mainly by the erosional history of the regional discharging rivers. Similar conclusions were drawn by DROPPA (1966) in his classical research in the Western Carpathians on the horizontal caves of Demänova and their correlation with the surrounding river terraces. In the eastern Alps HASEKE-KNAPCYK (1984) and KUFFNER (1994) could distinguish between three different major cave levels, derived from analysing the cave survey documents, that correspond with the old landsurfaces which have been determined by relief analysis. Through speleomorphological observations JEANNIN & BITTERLI (1998) identified even eight speleogenetic phases in the cave systems north of Lake Thun, Switzerland. These could be related to changes in the spring's position, which moved down due to tectonic uplift and simultaneous incision of the valleys.

In this study, we first identified the karstification levels in a catchment area by correlating surface and subsurface levels. The following correlation of these local karstification levels with regional landsurface levels of the Danube river and pre-alpine glaciations are presented in the discussion.

STUDY AREA

The catchment of the river Lauchert was selected as a study area (Text-fig. 1), because of the availability of a good data basis and previuos research on karst hydrology and river history (e.g. VILLINGER 1973, GOLWER 1978, SAUTER 1992). The river Lauchert is tributary to the river Danube. The entire catchment, with altitudes between 600 and 900 m a.s.l., is underlain by Late Jurassic carbonates and marls that form a steep escarpment in the north and gently dip south-east towards the river Danube and the Tertiary Molasse Basin.

The limestones and marls were deposited in a shallow sea connected to the Tethys. They are composed of bedded limestone-marl sequences that increasingly display massive bioherm facies in the Kimmeridgian (GEYER & GWINNER 1991). Sedimentation ceased in the early Tithonian when the plateau was slightly uplifted above the sea level. Some karst fillings indicate shallow karstification during Cretaceous and Early Tertiary time before the Molasse sea transgressed over the southern parts of the plateau during Late Oligocene and Early Miocene time sealing the paleo karst by sediments against further karstification. In the southern part of the study area some Miocene deposits are still preserved (red nodular limnic limestones and the 'Juranagelfluh', cemented limestone gravels of Late Miocene age; GOLWER 1978). In the Late Miocene and Pliocene an uplift and SW-NE tilting of the plateau took place and rivers started to incise up to 200 m as result of tectonic activities in the Rhine graben (GROSCHOPF & *al*. 1996, HÖTZL 1996). As a consequence of continuous entrenchment and progressive karstification the upper reaches of the rivers and the smaller tributary rivers have increasingly discharged into the subsurface and dried up. There are only a few relics of Pliocene sediments in the study area such as karst fillings and fluvial gravels of the early Danube river, which started to provide the regional hydraulic base level in the south during that time. The most northernly part of the surface catchment of the Lauchert river, that almost extents on to the steep escarpment that characterises the northern border of the Swabian Alb, discharges in the subsurface to the river Neckar which is tributary to the Rhine system (Text-fig. 1).

In the Pleistocene, the southern region was repeatedly affected by advances of the Alpine glaciers which largely controlled the fluvial history of the Danube river. The incision and aggradation phases of the Danube river are well known from various studies on terrace correlation and gravel analysis (e.g. VILLINGER 1998). Quaternary sediments in the tributary areas were mainly deposited in the valleys. While in the upper reaches the deposits consist mainly of loam and debris, in the main valleys of Lauchert and Fehla sand, gravel and clay from the last two ice ages are present which increase in thickness downstream. The most extensive glaciations in the Late Pleistocene ("Riss") overrode the Danube valley and the lower course of the Lauchert valley and left till deposits of several meter thickness behind (VILLINGER & WERNER 1985). The ice front dammed the tributary rivers from the north, which caused temporal flooding and lead to the deposition of glacio-lacustrine clay. In the last glaciation ("Würm") and the Holocene, the lower course of the Lauchert valley continued to fill up with sands, gravels, debris and loam between a few and about 10 meters (GOLWER 1978). In the Holocene some calcareous tufa barriers were precipitated up to a thickness of 15 m.

The majority of the study area belongs to the 'deep karst', a type of aquifer where the groundwater level is only controlled by the fluvial base level and therefore is always positioned above the sealing aquifer bottom (VILLINGER 1972). Only the most northerly part, near the escarpment, belongs to the 'shallow karst', where the water level is controlled by the topographic height of the impermeable aquifer bottom. However, in the Pliocene and Early Pleistocene, when the deeper karstification started, the carbonate plateau of the Swabian Alb extended further north and it can be assumed that the northern part of the study area still belonged to the deep karst at that time, i.e. draining south to the river Danube. SCHEFF (1983) already attempted to correlate the entrance position of caves and surface levels in parts of the upper Lauchert catchment. In contrast to our study, he did not analyse the horizontal cave passages, which are more reliable indicators, and did not compare the cave levels with changes in gradient of dry valleys and karstified zones in boreholes. Until now in the southern part of the Lauchert catchment such an investigation has not been performed, despite the importance of correlating karstification levels with incision stages of the river Danube as the regional base level.

SPATIAL EVOLUTION OF THE KARSTIFICATION IN THE LAUCHERT CATCHMENT

Materials and Methods

In this study, we distinguished karstification levels by identifying erosional base levels of the local and regional discharging rivers and cave levels, additionally using information on zones of intensive karstification in the subsurface, derived from boreholes. To reconstruct former karstification levels of the Lauchert catchment, we analysed the height distribution of different surface and subsurface indicators referred to the rock bed of the valleys.

Surface indicators

Surface indicators include the geomorphic analysis of remnant river terraces, distinct kinks in valley gradients, and remnants of former land surfaces (Text-fig. 2). The data were gained from own mapping, analysis of topographical maps and documentation of several drillings in the unconsolidated valley infill of the rivers Lauchert and Fehla.

The terrace fragments in the Lauchert catchment have been altimetrically mapped using an aneroid with an error range of 10 m. Measurements of higher accuracy are not advisable, since the terraces, especially the higher and older ones, have been exposed to erosion and dissection for long times. In the lower course of the Lauchert river terraces are partly buried by up to 40 m thick younger, unconsolidated sediments of the Late Pleistocene and Holocene. Information on buried terraces could be taken from different drillings in the valley sediments (e.g. VILLINGER 1973, GOLWER 1978). Hence, for the analysis of the height distribution, the rock bed of the valley was used as reference level.

The longitudinal profiles of the dry valleys have been drawn from the topographical map (1 : 25 000). Changes in gradient due to stratigraphical or tectonical influences (Lauchert graben) have been omitted and were not considered further.

Subsurface indicators

Subsurface indicators are conduits and cavities, which are related to preferential carbonate dissolution within the range of groundwater level fluctuations (BÖGLI 1966, PALMER 1987). Most caves of the Swabian Alb show more or less horizontal phreatic conduits occasionally looping up and down within a range of 40-60 m. This points to a solution in the vicinity of the water table.

In the study area more than 130 caves are known, but only 10 caves exceed 50 m in total length. The data basis is rather poor with respect to the total length of cave passages, which makes the identification of subsurface karstification levels as well as the characterisation of their spatial extension difficult. For reconstructing cave levels we only used horizontal sections of caves (minimum horizontal passage length 2 m) with a total cave extension of at least 5 m. The subsurface information was taken from own mapping of cave entrances and cave surveyings stored in the cave register of the Swabian Alb in Laichingen (managed by R. FRANK, speleo-club Laichingen). In general, these cave maps are drawn at a scale of 1:100, the small caves even at 1:50, and are well suited for analysis.

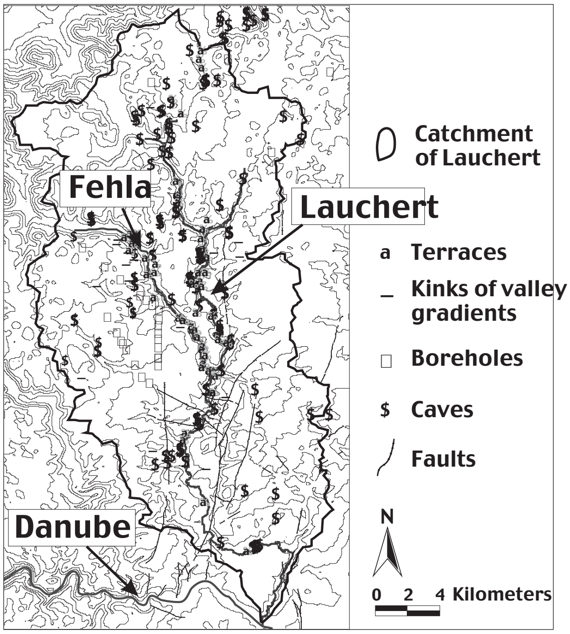

Fig. 3. Catchment area of the Lauchert river, with locations of terraces, kinks in the gradient of dry valleys, caves and boreholes

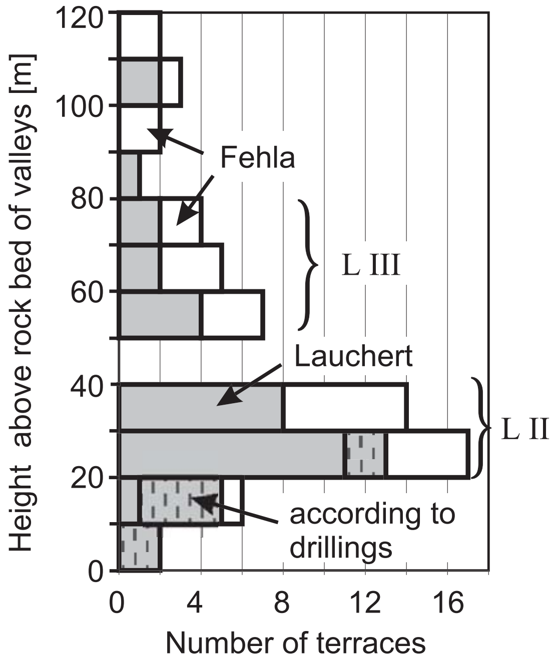

Fig. 4. Height distribution of terrace fragments above the rock bed of the valleys in the Lauchert catchment

In addition, deep core-drillings with detailed geological information have been surveyed for karstic cavities. They are available specifically in the central part of the catchment as result of a tunneling project for a water supply pipeline of the 'Bodenseewasserversorgung' (VILLINGER 1973). All karstic features in the core descriptions (the cores itself are not available anymore) have been identified and used to classify the boreholes in segments of high, slight or no karstification.

Features like open cavities, cavities filled with loam or limestone debris and strongly soluted joints and fissures have been classified as highly karstified, while only slightly soluted sutures, joints and fissures have been classified as slight karstification. Core segments that showed no solutional features have been classified as not karstified, as well as the loss of core material that solely resulted from strong fissuring, without showing signs of solution in the surrounding limestone.

The various localities of the surface and subsurface data are shown in Text-fig. 3.

Surface levels in the Lauchert catchment

Terraces

Terraces in the valleys of the Lauchert and its tributary rivers (Fehla, Seckach and Erpf) exist almost solely as rock terraces without any river deposits. Since the terraces in the lower course of the Lauchert river are partly buried by younger, unconsolidated sediments of the Late Pleistocene and Holocene (VILLINGER 1973, GOLWER 1978), for the analysis of the height distribution, the rock bed of the valley was used as reference level. The histogram shows two levels of river terraces at 20-40 m and 50-80 m above the reference level (Text-fig. 4). The uneven distribution with an underrepresentation of higher terraces may be partly caused by their long exposure to erosion.

Dry valleys

Characteristic for the Swabian Alb is its widely spaced network of dry valleys due to deepening of the fluvial base level. These dry valleys preserve the elevation and gradient of the last erosional event. In glacial periods these valleys partly regained their function as surface flowlines due to permafrost conditions, as could be proven by debris cones at their mouths into the Lauchert valley (VILLINGER 1973). During these short reactivations the lower courses eroded backward and smoothed the steep gradient in the lower courses towards the permanently river-bearing Lauchert valley. However, due to the limited amount of water available the gradient of the dry valleys was not equilibrated along their total length and distinct kinks in the longitudinal profile remained. At the position of the changes in the valley gradient also the valley shape changes. The cross sections change from wide and hollow

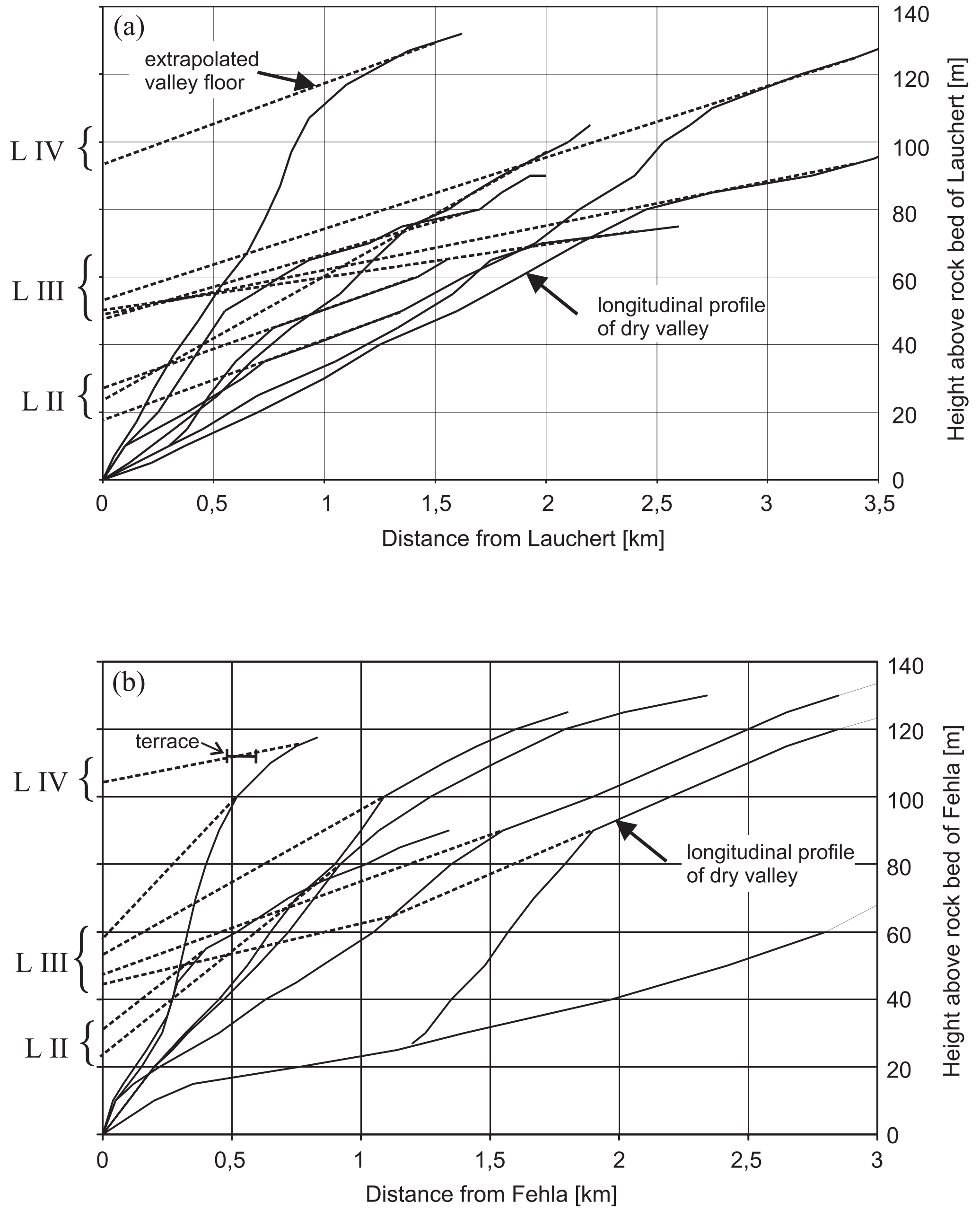

Fig. 5. Longitudinal profiles of the tributary dry valleys to the Lauchert (a) and Fehla (b), with characteristic kinks in the profiles (solid lines); dotted lines represent the extrapolation of the older, less inclined dry valley floors to the confluence with the major valleys of the Lauchert and Fehla

shaped in the upper courses to more narrow and V-shaped valleys in the lower courses.

The dry valleys that show distinct kinks of their gradient have been referred to the rock bed of the Lauchert and Fehla valleys and are presented in Text-fig. 5 as height-range diagrams. When extrapolating the upper, gentler gradient to the confluence with the main valleys of the Lauchert and Fehla, three former river levels can be reconstructed at 20-30 m, 45-60 m and 100-110 m.

Subsurface levels

Cave levels

Most caves in the study area are located at the valley side slopes of the main river valleys or smaller dry valleys, where they open to the surface. Despite some characteristic features of phreatic origin, an exact elevation of past vadose/phreatic transition points, as de-

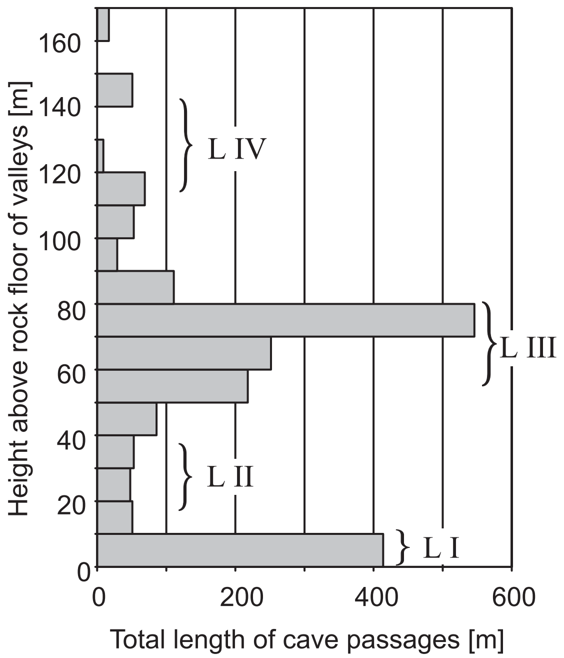

Fig. 6. Height distribution of horizontal cave passages above the rock bed of the valleys in the Lauchert catchment

monstrated by PALMER (1987), could not be defined due to the lack of larger cave systems. To identify certain cave levels, cave maps were used to determine the elevation of horizontal or slightly inclined cave passages. For cave levels the statistical distribution is highly dependent on the knowledge of cave locations and their accessibility. In the steep entrenched valleys the valley-side slopes are in the upper parts more or less free of thick debris cover in contrast to the lower parts of the slopes where possible cave entrances might be buried. Again, the distinguished cave levels were related to the rock bed of the major valleys. For the altimetric analysis only caves in direct vicinity of the river-bearing valleys have been accounted for, since only they can be correlated directly with the different erosion levels of the valleys without considering the changes of the water table along the groundwater flow path. But as shown in Text-fig. 3 most known caves in the study area do open up into the main valleys of the Lauchert and Fehla. The height distribution shows two cave levels at 0-10 m and 50-80 m (Text-fig. 6). The lowest level at 0–10 m is represented only by one single cave ('Hausener Bröller'), which is still active at times of high water level.

Karstification levels in boreholes

For the less dissected areas between the valleys without caves, boreholes are the only source to identify deep karstification. The analysed core descriptions have been classified in segments of high, slight or no karstification. A separation into distinct levels can be hampered by more or less continuous karstification from the top to the bottom. A differentiation between phreatic karstification and the subsequent vadose karstification will be attempted in the future. Some core-drillings showed different levels of karstification but a differentiation in 3-4 distinct karstification levels was not possible. Again the resedimentation of the valleys and the subsequent rise of water level above older levels caused an overlap of different karstification levels. Additionally, an increase in the water level fluctuations upgradient could be detected (SAUTER 1992), which has the effect of blurring the boundaries of karstification levels.

The identified karstification levels of boreholes have been correlated with cave levels and surface levels. In Text-fig. 7 the location of the different features is shown and a cross profile parallel to the groundwater flow lines illustrates the possible correlation of the different data sets. The major karstic segments in the boreholes, distributed at 40-90 m above the present water table, correspond well with the caves located on the same elevation and can be correlated with the karstification level of 50-80 m in the Fehla valley. The second, lower level, 10-30 m above groundwater level, is not very distinct and in some boreholes can already be influenced by recent groundwater level fluctuations.

Discussion: correlation of surface and subsurface karstic levels

The karstification levels as identified from the various data sources are summarised in Tab. 1 and in longitudinal cross sections through the Lauchert and Fehla valley (Text-fig. 8). The data consistently allow to distinguish three older karstification levels: L II at around 20-40 m, L III at around 50-80 m, and L IV at

Level	Fluvial terraces	River gradient	Caves	Boreholes
L IV	Old landsurface	100-110	100-120	(100-130)*
L III	(50-80)*	45-60	50-80	40-90
L II	20-30	20-40	(20-40)*	10-40
L I (Present)	Valley bottom	Valley bottom	0-10	Water level

* Not significant

Tab. 1. Correlation of karstification levels from terraces, river gradients, caves and boreholes, referenced to the rock base level in the Fehla and Lauchert valleys

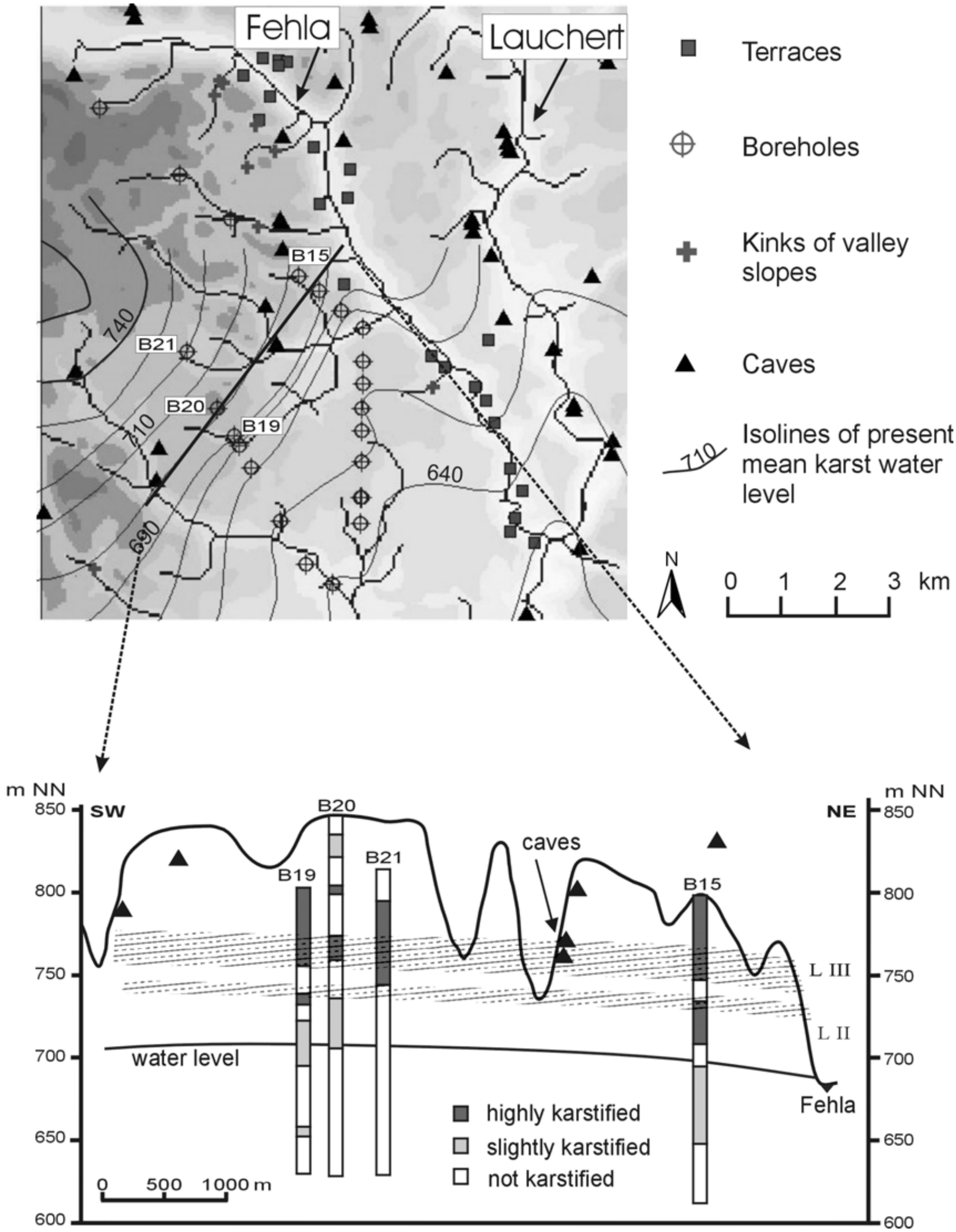

Fig. 7. Correlation of karstification levels in boreholes with caves in the Fehla subcatchment

around 100-120 m above the rock bed of the present valley. The different degree of markedness of karstification levels in the different data sets reflects the potential error inherent if only a single method is employed. As already pointed out, river terraces are less preserved at higher levels and cave statistics is not free of randomness due to hillside cut and discovery probabilities.

Text-fig. 8 shows the spatial correlation of the karstification features in height-distance diagrams as longitudinal profiles of the Lauchert and Fehla valleys according to their distance to the river Danube. In the

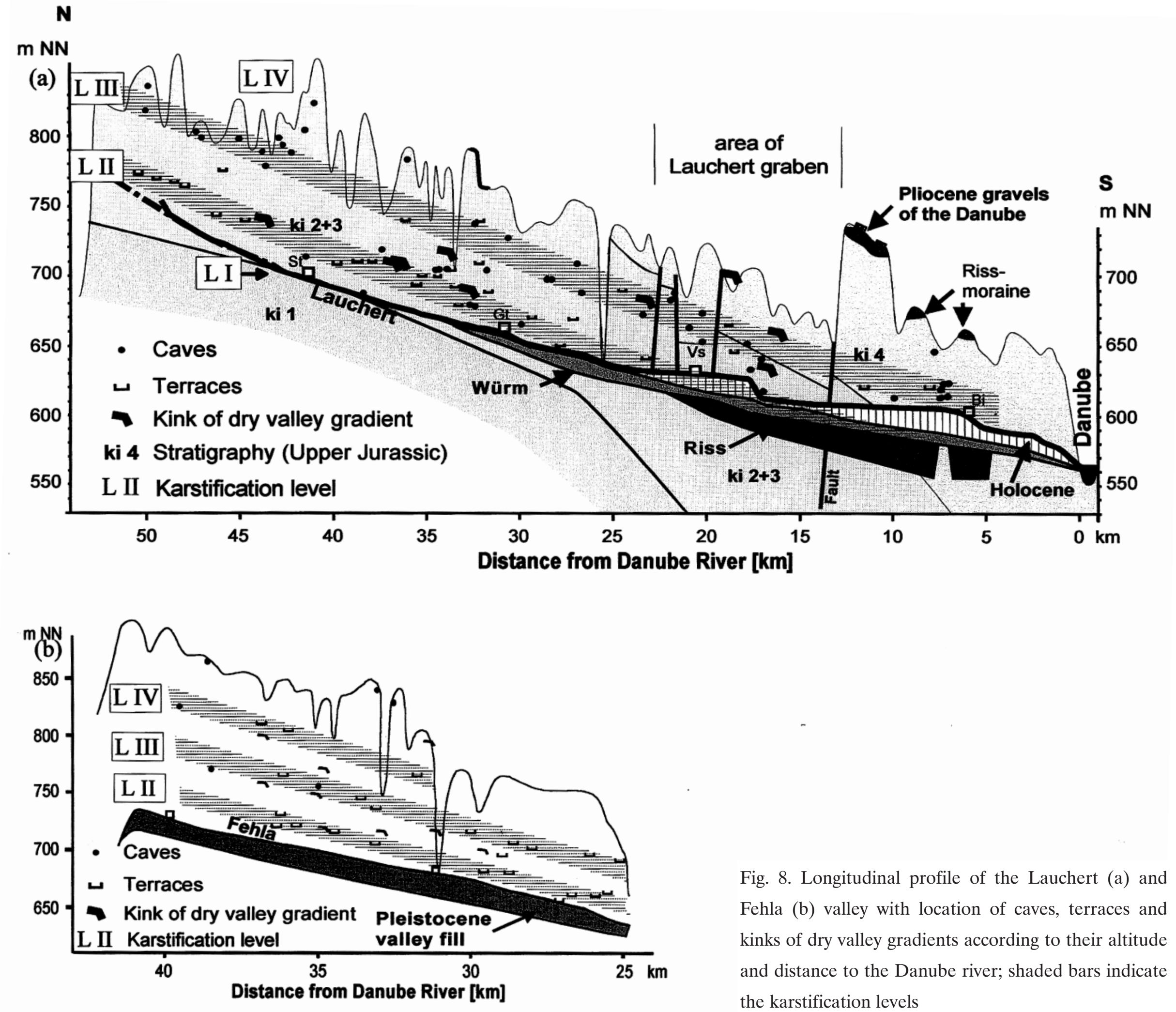

Fig. 8. Longitudinal profile of the Lauchert (a) and Fehla (b) valley with location of caves, terraces and kinks of dry valley gradients according to their altitude and distance to the Danube river; shaded bars indicate the karstification levels

lower course older and recent karstification levels overlap due to Late Pleistocene accumulation of lacustrine, glacigenic and fluvial sediments since the most extensive glaciation (“Riss”). Hence, the deepest incision dates back, at least, to the middle Riss, which corresponds to the age of ca. 0.4 Ma according to recent stratigraphic correlations by KELLER & KRAYSS (1999) with the Rhine glacier area. Since that time, the fluvial base level and thus the karstification level has repeatedly fluctuated by about 30 m but no further downcutting of the rock bed has taken place.

Level II represents a slightly higher karstification level before the deepest incision. Former workers correlated this level with the “Günz-Mindel“ interglacial or the “Mindel“ glacial of the Alpine foreland, respectively (SCHEFF 1983, VILLINGER 1986). The glaciations in the Alpine foreland are differenciated in the older “Decken” glaciations, comprising of the glaciations from the Earliest and Early Pleistocene, and the younger “Becken” glaciations, that cover the Middle and Late Pleistocene (ELLWANGER & *al.* 1995). KELLER & KRAYSS (1999) allocate the “Mindel” glaciation to the youngest “Deckenschotter” glaciations of the Early Pleistocene, which took place at a higher erosive level than the subsequent glaciations (“Riss” and “Würm”), which are characterised by the formation of overdeepened glacial basins in the Rhine glacier area and are referred to as the “Becken” glaciations. New magnetostratigraphic evidence from “Deckenschotter” sequences has shown inverse polarity and indicate a minimum age of 0.78 Ma (ELLWANGER & *al.* 1995). These newly revised glacial stratigraphy of the northern Alpine foreland have been correlated with the distinguished karstification levels in the Lauchert catchment, as it is shown in the schematic sketch in Text-fig. 9.

The pronounced horizon of L II indicates a longer stagnation of this fluvial base level, which fits well to the revised stratigraphic model of the Rhine glacier area,

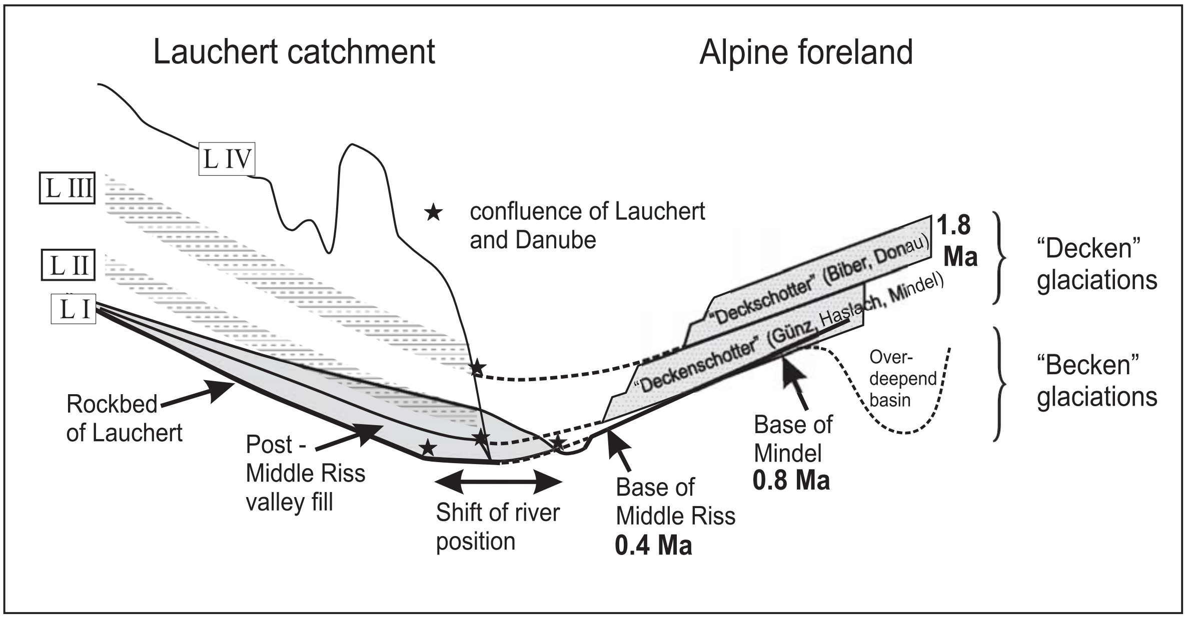

Fig. 9. Schematic sketch of the correlation of karstification levels in the Lauchert catchment and the glacial stratigraphical framework in the Alpine foreland

where the basis of the Early Pleistocene "Decken" glaciations ("Günz", "Haslach" and "Mindel") presumably have not changed much during a period of 1 Ma. Therefore the older correlation of L II with the "Günz-Mindel" interglacial and "Günz" glacial can, in principle, be confirmed but with a new and different perception concerning the age and time duration of this level.

Level L III is well preserved by numerous caves and represents the first major stagnation phase after the commencement of base level incision into the carbonate plateau during the Pliocene. Its formation at heights between 50 and 80 m above the rock bed of the Lauchert valley corresponds well with the highest gravel terraces in the upper Danube valley that comprise no more Alpine material (70-80 m above the present Danube river, VILLINGER 1986, 1998). In the Late Pliocene, at about 3 Ma, the Alpine tributaries to the Danube river from the south-west ("Aare-Donau") were cut, so that no Alpine clasts could reach the study area since then, but were deposited into the Sundgau west of Basel instead (BERTZ 1982, VILLINGER 1986). The level also corresponds with the "Deckschotter" glaciations ("Donau" and "Biber") of the Alpine foreland that show elevations of 45-70 m above the deep incision of the middle Riss (Text-fig. 9). According to faunal remnants, at least the younger parts of the "Deckschotter" sequence could be assigned to the Tegelen, which gives a minimum age of 1.6-1.8 Ma (RÄHLE & BIBUS 1992, ELLWANGER & *al*. 1995). That assigns L III to an age between 1.8 and maximum 3 Ma (Earliest Pleistocene and Late Pliocene).

Consequently, L IV represents a Pliocene karstification level. This uppermost karstification level L IV is only constrained by few relics scattered in the area and is therefore not marked as a continuous level in Text-fig. 8. However, some of the caves and remnants of old landsurfaces can be correlated with the former coast line of the Miocene Molasse sea, which is still visible in the landscape (GEYER & GWINNER 1991), and the Mio-Pliocene gravels of the early Danube. These gravels, the so-called "Pliozäne Donauschotter", still contain Alpine clasts and can be found on the southern plateau of the Swabian Alb (DONGUS 1977, SCHEFF 1983). Thus, a minimum age of ca. 3 Ma can be assigned to L IV. The maximum age corresponds to the regression of the Molasse sea at around 15 Ma, however, some million years must be allowed for the removal of the formerly deposited Oligocene to Miocene sediments.

CONCLUSIONS

Based on the correlation of karstification features and the integration into a revised regional stratigraphic framework (Text-fig. 9), the genesis of the deeper karst of the Swabian Alb can be summarised as follows:

- up to 15 Ma to ca. 3 Ma: Karstification started to deepen but was still relatively shallow. In the Late Miocene the Aare-Danube river developed as regional base level and started to entrench into the carbonate plateau of the Swabian Alb that was tectonically uplifted. The corresponding karstification level is L IV (100 to 120

m above the rock floor of the present valleys). Nowadays the related caves are only preserved in topographical heights.
- ca. 3 to 1.8 Ma: The incision proceeded until the height of L III was reached. Karstification reached a depth of up to 100 m. The Alpine Aare river was cut from the Danube river in the Late Pliocene (at about 3 Ma) and afterwards no Alpine gravels reached the study area.

- 1.8 to 0.8: Ma: After some stagnation at L III, incision continued at almost the same mean rate, in the order of about 60 mm/ka, than in the period before. However, effective incision rates may have been much higher, because good correlation exists between L II and the long persistence of the erosional level of the "Deckenschotter" glaciations in the Rhine glacier area. Karstification reached now a depth of up to 150 m at L II.

- ca. 0.8 to 0.4 Ma: After the onset of the deep eroding "Becken" glaciations a further pulse of incision took place. At around 0.4 Ma, in the forehand of the maximum glacial advance in the middle Riss, the maximum lowering of the karstification level was reached by L I. This level is still active in the upper reaches of the study area.
- 0.4 Ma to 0: the most extensive glacier advances in the middle Riss overrode the Danube river, and tributaries from the north were dammed. Glacial, glacio-lacustrine and fluvial sediments were deposited towards the Danube river which partly sealed conduits and cavities. In the subsequent youngest Würm glaciation the infill of the lower courses of the tributaries continued. Therefore, the modern, Holocene karstification level is elevated in the south, but still corresponds to L I in the north.

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