Abstract The Swabian Alb formed by an Upper Jurassic carbonate sequence is the most extensive karst area of Germany. The western part is crossed by the upper Danube River. It represents an old, mainly Pliocene, drainage system that is now restricted by the young Rhine system. The low base level of the upper Rhine graben causes a strong headward erosion. Since the Upper Pliocene, the Danube has lost more than 90% of its headwaters. The underground Danube–Aach karst system of the western Alb represents the last capture of the Rhine, leading periodically to a complete loss of water in the upper Danube. The seepage of this water, together with the huge karst catchment area, supplies the strong discharge of the Aach Spring, forming the largest spring of Germany with an average discharge of 8.5 m$^3$ s$^{-1}$.

Key words Aach system · Karst · Germany

Introduction

Germany has several karst areas in the outcrops of Paleozoic, Mesozoic, and Tertiary limestone and gypsum that vary in size and importance. The largest closed karst area is the Swabian Alb between the Neckar and the upper Danube rivers (Fig. 1). It is a part of the South Germany cuesta landscape and is formed by the outcrop of the Upper Jurassic carbonate sequence. This flat mountain ridge east of the Black Forest forms the northern margin of the Molasse basin, and to the southwest it passes into the Swiss Jura Mountains. The Alb extends from SW to NE more than 200 km, and the width is about 40 km. The cuesta faces northwest, and its steep escarpment, the so-called “Albtrauf,” rises from 600 m in the foreland to 1000 m asl, from where the Alb plain dips gently to the southeast.

This carbonate, flat-topped ridge exhibits moderate to intensive karstification. The most pronounced morphological feature is the widely spaced network of dry valleys, which are in sharp contrast to the dense drainage network in the clayey foreland of the Alb. Numerous karst depressions, dolines, cave systems, and sinter formations underlie the karst. Active sinkholes and karst springs demonstrate the hydrogeologic efficiency of the underground drainage system discharging towards the Danube River.

The young, dynamic morphology is determined by the relative position of the Danube and Rhine River drainage systems. Favored by the deep base level in the upper Rhine graben (Fig. 1), the Rhine River gradually captures more of the old Danube drainage area. This affects not only the surface drainage but also the groundwater and has led to one of the most spectacular karst phenomena of Germany, the “Donauversickerung,” the loss of the Danube water in the western part of the Swabian Alb to the Aach spring, a tributary of the Rhine system. The hydrogeologic details of this phenomenon and its development are described herein.

Geological setting

The Swabian Alb is part of the main tectonic block of southern Germany (Geyer and Gwinner 1984, 1986). This area is associated with one of the Variscian orogenic zones, which was folded, overthrust, metamorphosed, and intruded by granitic plutons. During the Upper Carboniferous and Permian, the area was uplifted and eroded forming the basement, which now crops out with granite and gneiss in the Black Forest.

The new epicontinental sedimentary cycle started during the Lower Triassic with a sandy continental sequence. Marine carbonates with an evaporitic intercalation succeeded during the Middle Triassic. In the Upper Triassic,
continental influence prevailed. During the Jurassic, clayey, marly, and carbonaceous sediment sequences were deposited. The most conspicuous sequence is the more than 300-m-thick Upper Jurassic carbonates. These consist of light-colored, regularly bedded limestone and marl that pass partly into massive algal-sponge limestone with tower-like structures.

At the end of the Jurassic, the area of the Swabian Alb became subaerial and vast parts have remained so. Strong weathering and karstification occurred on the flat carbonate landscape, especially during the Cretaceous and Early Tertiary with the warm and humid climate. The topography of the recent landscape originated from the tectonic events of the Middle and Late Tertiary. In the south, the overthrusting of the Alps caused the foredeep basin of the molasse. With the table-like uplifting of the Black Forest in connection with development of the upper Rhine graben, the Swabian Alb tilted southeastward, toward the Molasse basin. The Molasse basin then controlled further orientation of the drainage pattern.

Development of Danubian drainage pattern

With the tilting of the Swabian Alb during the mid-Tertiary, a system of consequent streams was formed. These pre-Danube rivers followed the slightly dipping surface toward the Molasse basin (Schreiner 1974). After the filling of the basin, mainly due to the sediments derived from the Alps in the south, the sea retreated eastward in the Late Miocene. The drainage channels followed the retreating sea, and the early Danube was formed during the Late Miocene and Early Pliocene (Fig. 2). It comprised a huge catchment area, including that of the Aare, along with vast parts of the western Swiss Alps (Wagner 1961; Villinger 1986). The early Danube River drained more than 20,000 km² in one section of the Swabian Alb, which now has a drainage area of 900 km² (Hötzl 1973).

During the Pliocene, tectonic displacement and additional uplifting of the northwestern part of the Alb caused a gradual movement of the Danube toward the southeast. Later, it started to dissect the Upper Jurassic limestone, and by the Middle Pliocene it had reached a base level of 200 m below the old surface. The remnants of this old meandering valley are represented as meander-scar terraces about 50 m above the recent valley floor (Wagner 1961). Only the main tributaries within the Alb followed this deep dissection. Because of the increasing karstification, larger areas of the new Alb high plains began draining into the subterranean discharge systems. Vertical tectonic displacements during the Pliocene (Illies 1965) caused additional critical changes in the drainage pattern outside the Alb. In the west, the Saone River, a tributary of the Rhine River, is captured by eastward erosion—one of the main headwaters of the early Danube, the Aare River. Therefore, the main part of the former upper Danube catchment along with vast parts of the Swiss Alps was draining westward through the Burgundian gate directly to the Mediterranean Sea. In the Late Pliocene, the Danube catchment area was reduced gradually but still included the Alpine Rhine and the early Eschach River with its catchment in the central Black Forest, now part of the Neckar system (Fig. 2).