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Water Resources – Drinking Water

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Abstract

In Austria, geologists play an important role in exploring and protecting groundwater resources. Concerning the development of investigation methods, Austrian hydrogeologists did pioneering work mostly in the field of tracer techniques. This is demonstrated by some representative examples. Four examples concern the Northern Calcareous Alps, which bear enormous karst groundwater resources. These are the Mühlau springs (water supply of the state capital Innsbruck), the Dachstein massif, the Rax-Schneeberg region (First Vienna Water Line) and the Hochschwab region (Second Vienna Water Line). One example concerns the largest pore groundwater aquifer of Austria, the so-called Mitterndorf depression. Here enormous problems with groundwater contamination are present.

Introduction

Due to the high precipitation in Alpine regions, Austria is a water rich country. In higher locations the precipitation amounts to about 2000 mm/a (BAUMGARTNER et al., 1983). Although Austria covers an area only of about 84.000 km^3, it produces an average outflow of 55 billion m^3/a (BUNDESMINISTERIUM FÜR LAND- UND FORSTWIRTSCHAFT, www.bmlf.gv.at). This corresponds to an average chatchment yield factor of about 21 ls^{-1}km^{-2}.

In Austria, high productive groundwater resources are located within the carbonate rich units of the Alps, in particular within the Northern Calcareous Alps and within expansive Quaternary gravel-bodies of valleys and depressions (Fig. 1). The landscape of the calcareous Alpine regions is characterized by the occurrence of extensive and frequently strongly karstified mountain ranges which form productive karst aquifers. These karst aquifers contribute a considerable part to the drinking water supply of Austria, e. g. for the cities of Vienna, Innsbruck and Salzburg. Particularly extensive Quaternary pore aquifers are located along the valleys of the Danube, Mur, and Inn, as well as in the Vienna basin. For example, the state capitals Linz and Graz receive their drinking water for the most part from such aquifers. Due to dense settlement and industry on the one hand, and agriculture on the other, these Quaternary pore aquifers are exposed to a high risk of contamination. In general, within Tertiary sediments of the Molasse zone and the intra-alpine basins, as well as within the geological units of the Bohemian Massif, Rhenodanubian Flysch Zone, Graywacke Zone and Central Zone of the Eastern Alps only local aquifers with limited productivity occur.

The following chapters discuss some important ground- and springwater occurrences in Austria (Fig.1). Within the Northern Calcareous Alps these include the Mühlau springs to the north of Innsbruck, the Dachstein range in the center of Austria, and the First and Second Vienna Water Lines in the Rax-Schneeberg and Hochschwab region respectively. The vast pore aquifer of the Mitterndorf depression is situated within the southern Vienna basin. The following chapters should bring some representative contributions of hydrogeologists to groundwater exploration and protection in Austria. The pioneering work on the field of tracer techniques in the Dachstein region is outstanding.

Mühlau springs

The Mühlau springs are the prime source of water for the state capital Innsbruck. They represent one of the big spring groups which discharge the Karwendel range, a 40 km long and 20 km wide carbonate massif to the north of Innsbruck (Fig. 1). In the Karwendel range, the most important water-bearing formation is the Wetterstein Limestone (Ladinian to Early Carnian). This is due to the wide lateral extent, thickness (in the central Karwendel its thickness reaches 3000 m; Fig. 2), and high storage capacity caused by intensive fracturing., In the Karwendel range, according to HEISSEL (1993), karst is, as a rule, just slightly developed.

The waterworks of Mühlau have been in operation already since 1890. In 1953 new galleries were completed which capture the water deeply in the mountain. They consist of three infiltration galleries (Wurmbach, Klammbach, and Rum galleries) and one collector gallery (Fig. 3). The overall length of these galleries amounts 1663 m. The actual total discharge of the captured Mühlau springs varies between 500 and 2000 l/s, in the course of which this amount is distributed to the mentioned infiltration galleries in the ratio of 1 to 2 to 7. That means that the major part of the dis-

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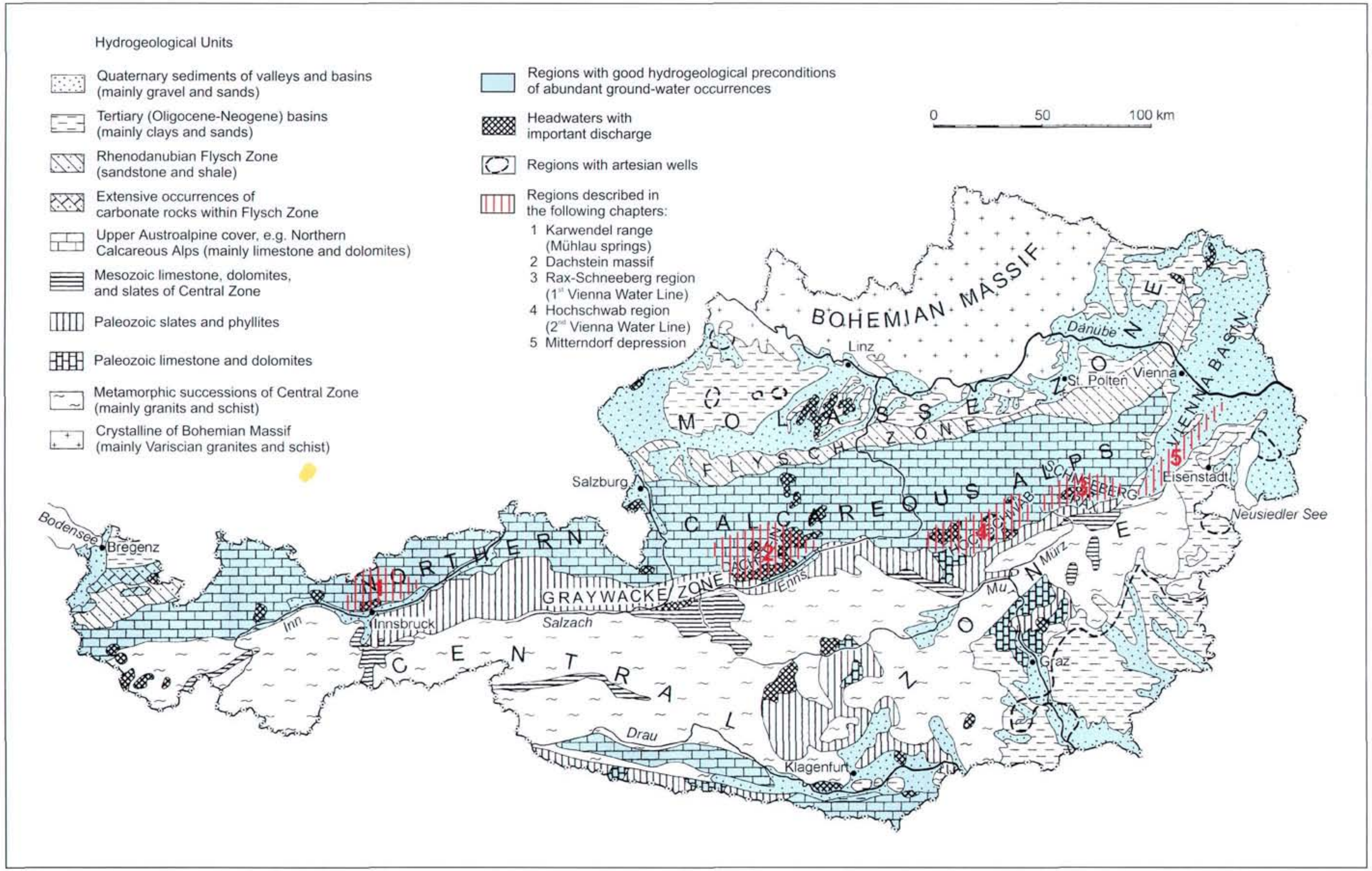


Fig. 1
Hydrogeological units of Austria (GATTINGER, 1980).

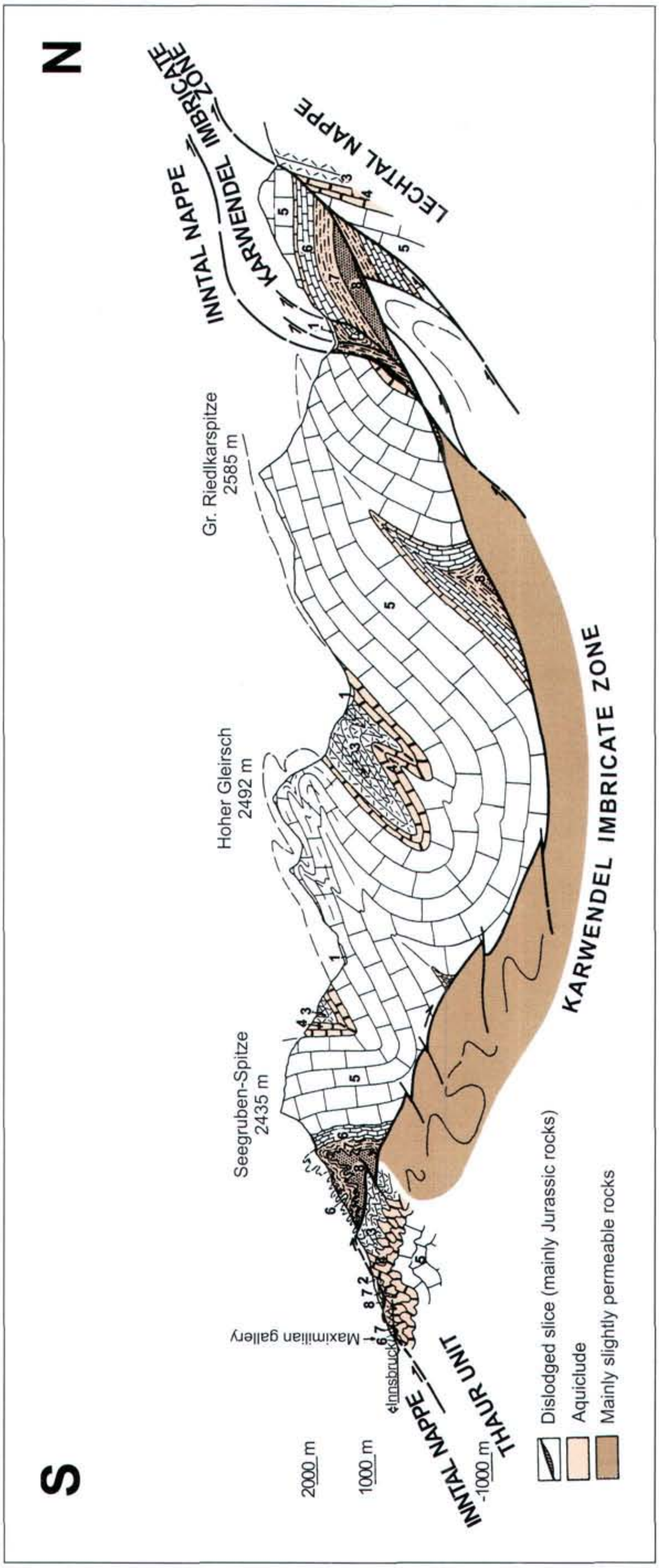


Fig. 2
Hydrogeological cross section of the Karwendel range (HEISSEL, 1993). The position of Mühlau springs corresponds to the Maximilian gallery. For legend, see Fig. 4.

charge infiltrates into the Rum gallery which is the longest one (HEISSEL, 1993).

In 1989, HEISSEL (1993) remapped the geological situation of the galleries. The result of these investigations is shown in Figs. 3 and 4: The Mühlau springs rise near the bottom of the Inntal nappe. The aquiclude is built by low permeable basal strata of Inntal nappe and the uppermost part of Thaur unit (according to HEISSEL, 1993, the Thaur unit is a part of the Karwendel imbricate zone; Fig. 2) and by the fault gouge zone in between these tectonic units. Within the Inntal nappe, the sealing strata are Alpine Bunter (an alternation of Skythian sandstone and shale) and the Reichenhall Formation (a heterogeneous sequence of carbonates, shale and rauhwacke; Early Anisian). Within the Thaur unit, the aquiclude consists of Raibl Formation (an alternation of carbonates and shale of Carnian age).

In the galleries, the infiltration happens chiefly within the Alpine Muschelkalk, a heterogeneous Anisian limestone formation. Together with the overlying thick Wetterstein Limestone (Ladinian to Early Carnian), these carbonates build the Aquifer of Mühlau springs (Fig. 4). The waters of the Wurmbach and Klammbach galleries must have been in intensive contact with the Raibl Formation of the Thaur unit (Carnian), as indicated by a distinct concentration of SO_4^{2-}. In the recharge area of Mühlau springs, this Formation contains gypsum (HEISSEL, 1993). From a geological point of view, HEISSEL (1993) suggested that the catchment area of the Mühlau springs amounts 25 km². To the north he restricted the intake area by the deep syncline in the north of Hoher Gleirsch which includes the sealing Raibl Formation of the Inntal nappe (Fig. 2).

In the years 1989 and 1990, Mühlau springs were subjected to an intense hydrochemical and isotope hydrological monitoring program (RAMSPACHER et al., 1992). The aim of this investigations was to determine the intake area and the mean residence time of the outflow of Mühlau springs, as well as to estimate the total storage volume from a hydrological point of view. From water balance considerations, RAMSPACHER et al. (1992) concluded that the discharge of Mühlau springs corresponds to a recharge area of about 30 to 36 km². This is based on the assumption of a mean outflow of 1370 l/s. Corresponding to RAMSPACHER et al. (1992), the hydrological data indicate a recharge area reaching further northward than deduced by HEISSEL (1993).

The phenomenon that the recharge area estimated by water balance is larger than that based on geology, occurs also in other regions of the Northern Calcareous Alps. There are two possible reasons for this effect: The first results from the difficulties in measuring representative precipitation heights in Alpine regions. The second is the fact that geological barriers are not completely tight.

According to RAMSPACHER et al. (1992), *from the relatively low* $\delta^{18}O$-fluctuations (Fig. 5), i. e. the damping of the input signal, which is given by precipitation, the mean residence time of Mühlau springs amounts more than 6 years. By way of the exponential model, the Tritium-contents show that the waters from the Wurmbach and Klammbach galleries (8 to 10 years) are younger than those of the Rum gallery (11 to 15 years). The Rum gallery captures a somewhat deeper, and therefore older, groundwater. Based on an average mean residence time of about 12 years and on a mean total discharge of 1370 l/s, RAMSPACHER et al. (1992) estimated a storage volume of the aquifer of the Mühlau springs of about 516 million cubic meters. Under the assumption of an aquifer thickness between 300 and 500 m, they further deduced a porosity of about 3 to 5%.

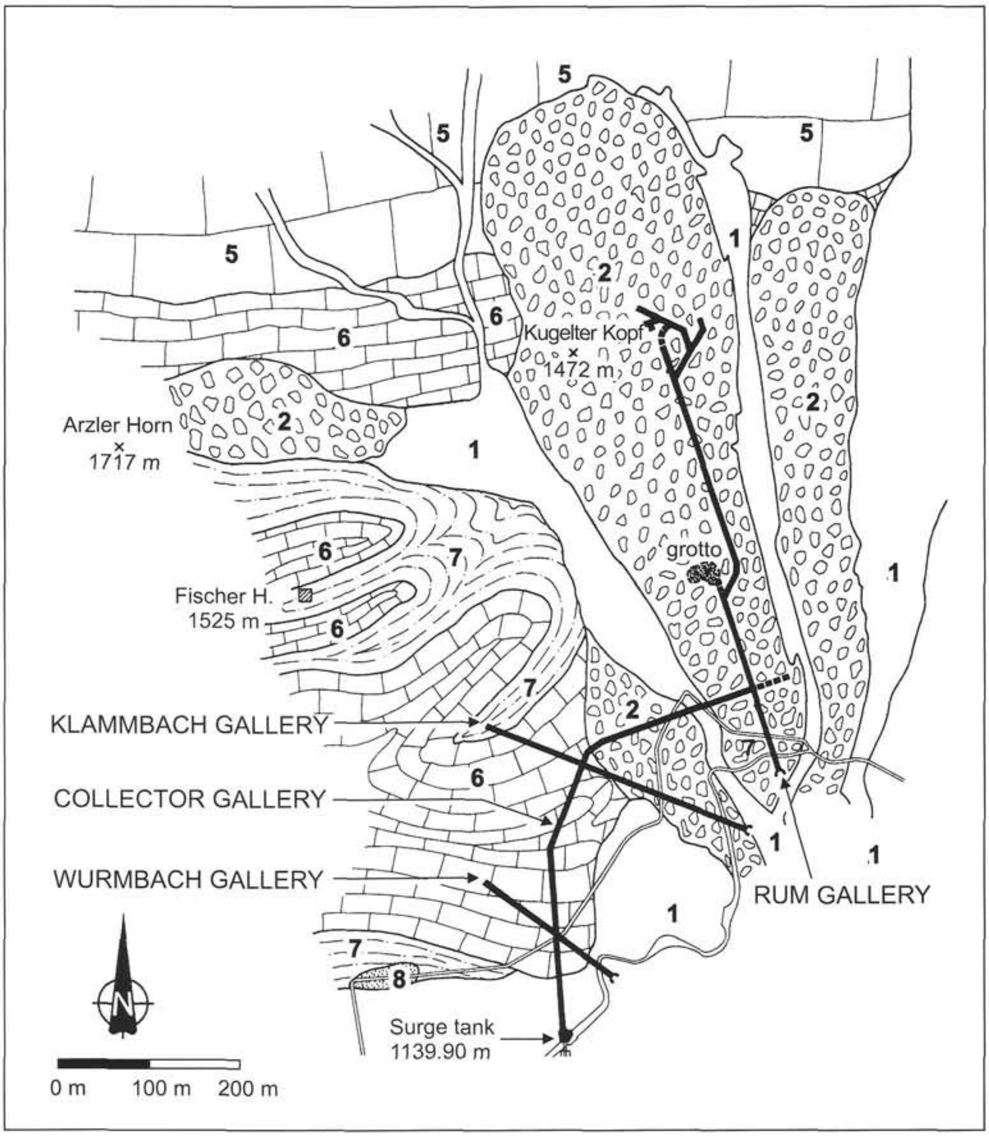


Fig. 3
Geological sketch of the environment of Mühlau springs (HEISSEL, 1993). For legend, see Fig. 4.

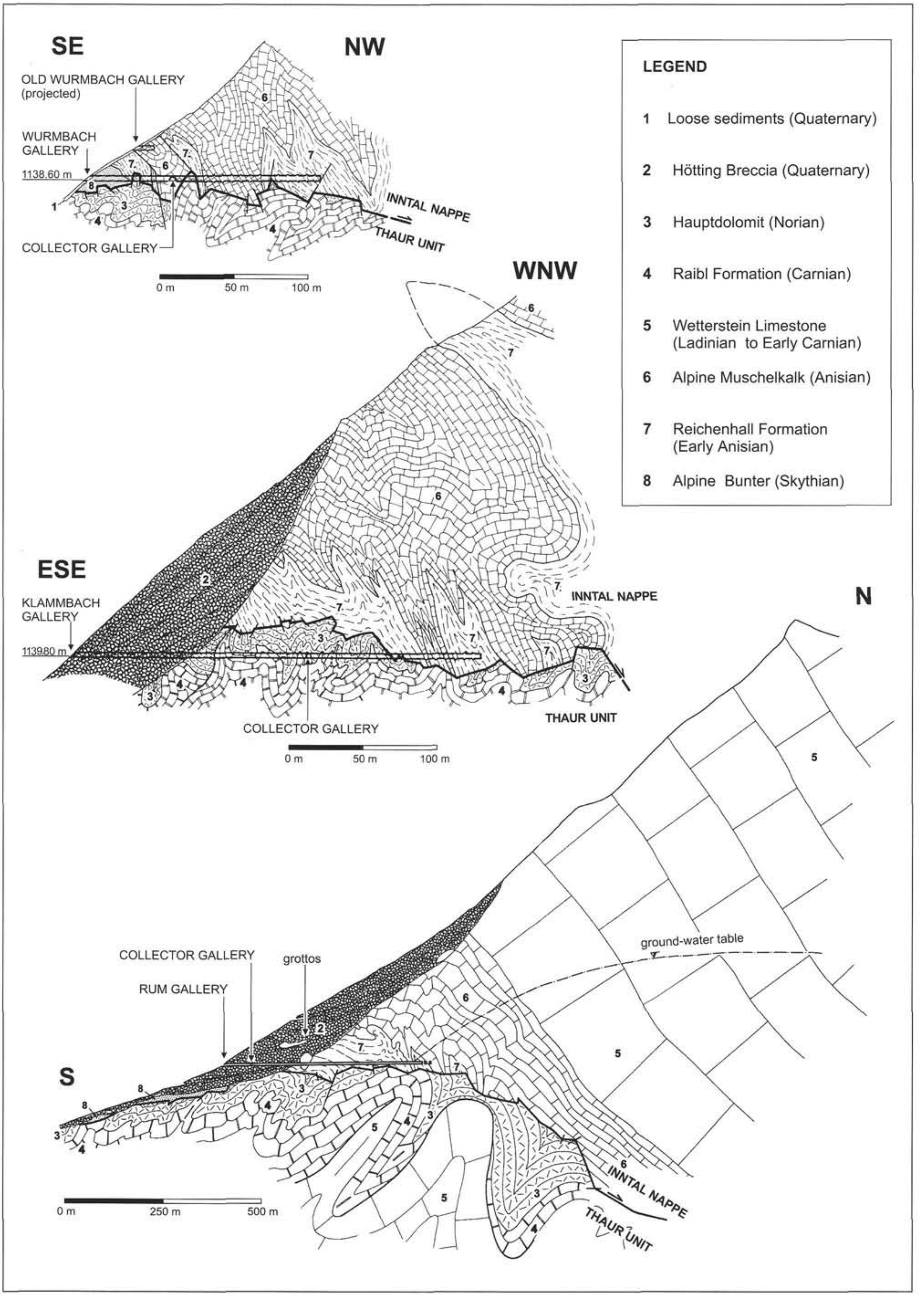
Dachstein Massif

The Dachstein massif (Fig. 1) represents one of the largest karst plateaus in Austria. It covers an area of 40 km in length by 20 km in width and reaches an altitude of 2995 m above sea level. The Dachstein massif consists of a thick northward dipping Triassic carbonate sequence. This region, the site of the prehistoric salt mine of Hallstatt belongs to the World Heritage of UNESCO.

The Dachstein massif has been extensively explored by tracer tests. These investigations have been an important contribution to the progress of tracer techniques. This concerns both *Lycopodium* spores tracers and fluorescence tracers. In the Dachstein region *Lycopodium* spores were used even in 1953, by MAYR (1956). He marked a swallow hole on the shore of the lake Hinterer Gosausee (point F2 in Fig. 6) and found out connections to the karst spring Waldbachursprung (point E1) in the northeast and to the karst springs in the southern Gosau valley (point F4) in the northwest. In times of a high groundwater level this swallow hole acts as spring.

Due to a new method of dying *Lycopodium* spores in different colors (DECHANT, 1959), it became possible to apply *Lycopodium* spores simultaneously to several places within one area. In 1956 and 1958, spacious spore tracer investigations were carried out in the whole Dachstein massif (MAURIN and ZÖTL, 1959). The results of these tracer tests

Fig. 4 →
Geological cross sections of Wurmbach, Klammbach, and Rum galleries (HEISSEL, 1993). For location, see Fig. 3.


SE
NW
OLD WURMBACH GALLERY (projected)
WURMBACH GALLERY
1138.60 m
INNTAL NAPPE
THAUR UNIT
COLLECTOR GALLERY
0 m 50 m 100 m
WNW
ESE
KLAMMBACH GALLERY
1139.80 m
INNTAL NAPPE
THAUR UNIT
COLLECTOR GALLERY
0 m 50 m 100 m
N
S
ground-water table
COLLECTOR GALLERY
grottos
RUM GALLERY
INNTAL NAPPE
THAUR UNIT
0 m 250 m 500 m
LEGEND
1 Loose sediments (Quaternary)
2 Hötting Breccia (Quaternary)
3 Hauptdolomit (Norian)
4 Raibl Formation (Carnian)
5 Wetterstein Limestone (Ladinian to Early Carnian)
6 Alpine Muschelkalk (Anisian)
7 Reichenhall Formation (Early Anisian)
8 Alpine Bunter (Skythian)

led to the conclusion that the subsurface drainage of the Dachstein massif runs from the central region radial to all directions (Fig. 6).

Extensive fluorescence tracer tests were carried out in 1984, 1985, and 1986, by BAUER (1989). They showed that the subsurface runoff of the Dachstein massif is essentially north-directed (Fig. 7) and not, as MAURIN and ZÖTL (1959) suggested, radially. In only two cases a fluorescence tracer was found in springs on the southern side of the Dachstein massif (points l and m in Fig. 7). BAUER (1989) assumed a subsurface drainage divide located in the southernmost part of the Dachstein massif. In his opinion, many of the connections found out by spore tracer tests were not a result of subsurface runoff but a result of misplacement of spores. He took a connection for granted only if the tracer concentration in spring water had shown a tracer breakthrough curve.

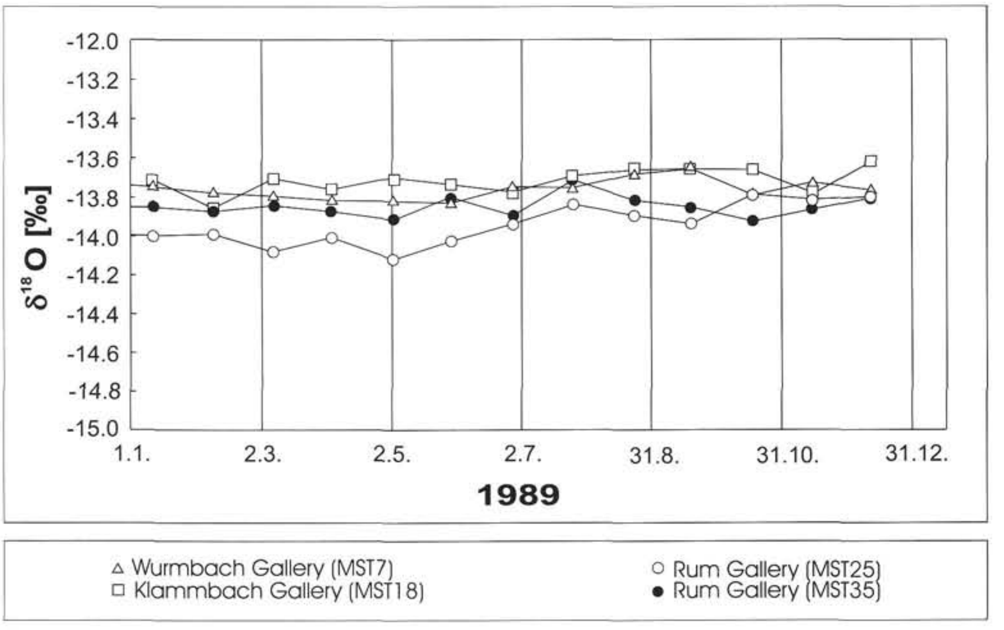


Fig. 5
$\delta^{18}O$ variation of outflows of Wurmbach, Klammbach, and Rum galleries (RAMSPACHER et al., 1992). By means of an aquifer discharge model, a mean residence time of more than 6 years could be derived.

In 1990, the Federal Environment Agency (Vienna) carried out two further fluorescence tracer tests in the western Dachstein region (HERLICSKA and HOBIGER, 1991). The aim of these investigations was to explore the recharge area of karst springs located in the southern Gosau valley (points c, d, e, and q in Fig. 7) and west of Hallstatt (point f) in detail. It became apparent that the inflow areas of these two spring groups overlap strongly. The interstitial velocities during high flow conditions were considerably higher than during low flow conditions.

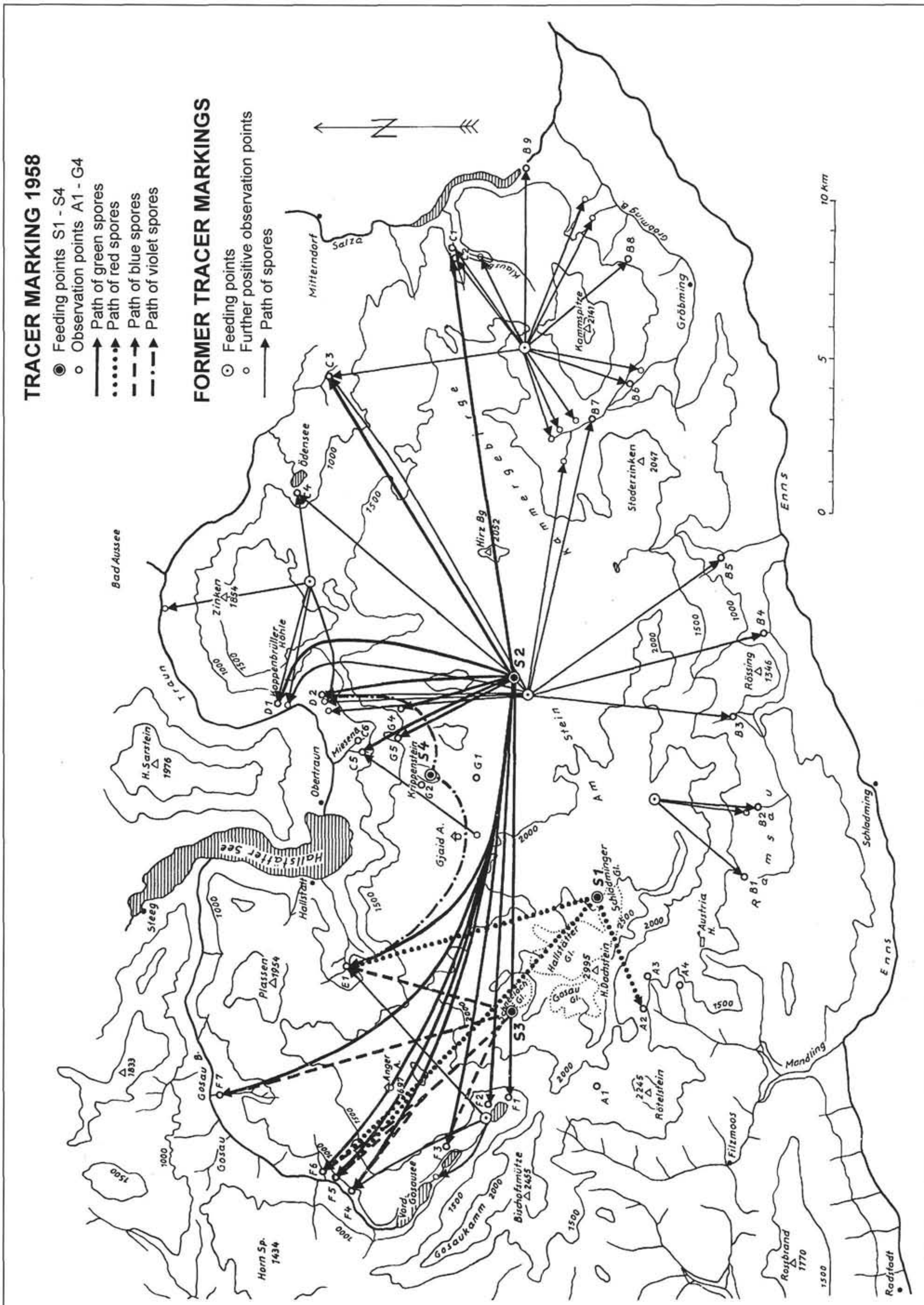
An extensive spring monitoring program was conducted by the Federal Environment Agency in the years 1991 to 1994, the so-called "Karst-Water Dachstein" project (HERLICSKA, 1994; SCHEIDLEDER, 2000). In this context, a supplementary geological mapping was carried out by the Geological Survey of Austria (MANDL, 2000). Based on the new hydrographic, hydrochemical, isotope hydrological and geological informations, the understanding of the subsurface runoff in the Dachstein massif could be considerably improved (TRIMBORN et al. 2000; SCHUBERT, 2000). In the following, the results are summarized.

The Dachstein massif consists of a generally northward dipping Triassic carbonate sequence, which belongs to the Dachstein nappe (Fig. 8). The basal aquifuge of these carbonates is built by Permoskythian and Early Paleozoic slaty-siliciclastic strata of different tectonic origin. The upper part of the carbonate sequence consists of up to 1000 m thick, strongly-karstified Norian Dachstein Limestone. This limestone forms the main aquifer in the Dachstein region; within it, a rapid subsurface runoff toward the big karst springs in the north takes place (in the following called: the northern springs). A representative example is the Waldbachursprung (number 201 in Fig. 8). With 20 to 12,000 l/s, it is the biggest karst spring of the Dachstein region. The lower part of the carbonate sequence comprises a 1000 m thick, Anisian to Early Carnian dolomite succession (mainly Wetterstein Dolomite). Relating to the overlying Dachstein Limestone, the dolomite succession forms an aquitard. In the south of the Dachstein Massif, in the Enns valley, the dolomites crop out extensively. Here, several small springs rise within the range of the base of the dolomites (in the following called: the southern springs).

In the areas of the Plassen and Rettenstein mountains, as well as in the surroundings of Bad Mitterndorf, tectonic blocks consisting of a heterogeneous sediment sequence appear lying upon the Dachstein nappe. This uppermost tectonic unit is called the Hallstatt zone. For example, the Permian evaporites of the salt mine in Hallstatt (Haselgebirge) belong to it. The springs rising in the environment of these tectonic blocks have mostly local recharge areas. As a consequence of the heterogeneous bedrocks, they have various chemistries.

In the following, the characteristics of the northern springs (limestone type) and the southern springs (dolomite type) are considered. Fig. 9 contains the corresponding discharge- and $\delta^{18}O$-hydrographs, as well as hydrochemical discrimination diagrams. The northern springs are characterized by high Ca^{2+}/Mg^{2+}-ratios (calcareous inflow area) and strongly varying discharges and $\delta^{18}O$-concentrations (rapid subsurface runoff). Apart from the Baumbach spring (number 110 in Fig. 8), the longer $\delta^{18}O$-hydrographs of the northern springs indicate a runoff composition with 21 to 28% of a younger component (mean residence time

Fig. 6 →
Results of the spore tracer tests in 1958 and earlier (MAURIN and ZÖTL, 1959). The spore tracer tests led to the assumption of a radial karst discharge.


TRACER MARKING 1958
Feeding points S1 - S4
Observation points A1 - G4
Path of green spores
Path of red spores
Path of blue spores
Path of violet spores
FORMER TRACER MARKINGS
Feeding points
Further positive observation points
Path of spores
Bad Aussee
Mitterndorf
Salza
Ödensee
Traun
Obertraun
Hallstätter See
Hallstatt
Steeg
Gosau
Gosausee
Gosaukamm
Bischofsmütze
Schladming
Gröbming
Enns
Mandling
Filzmoos
Radstadt
Rötelstein
Rössing
Stoderzinken
Kammspitze
Zinken
Koppenbrüller Höhle
Krippenstein
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Horn Sp.
Rossbrand
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Am Stein
10 km

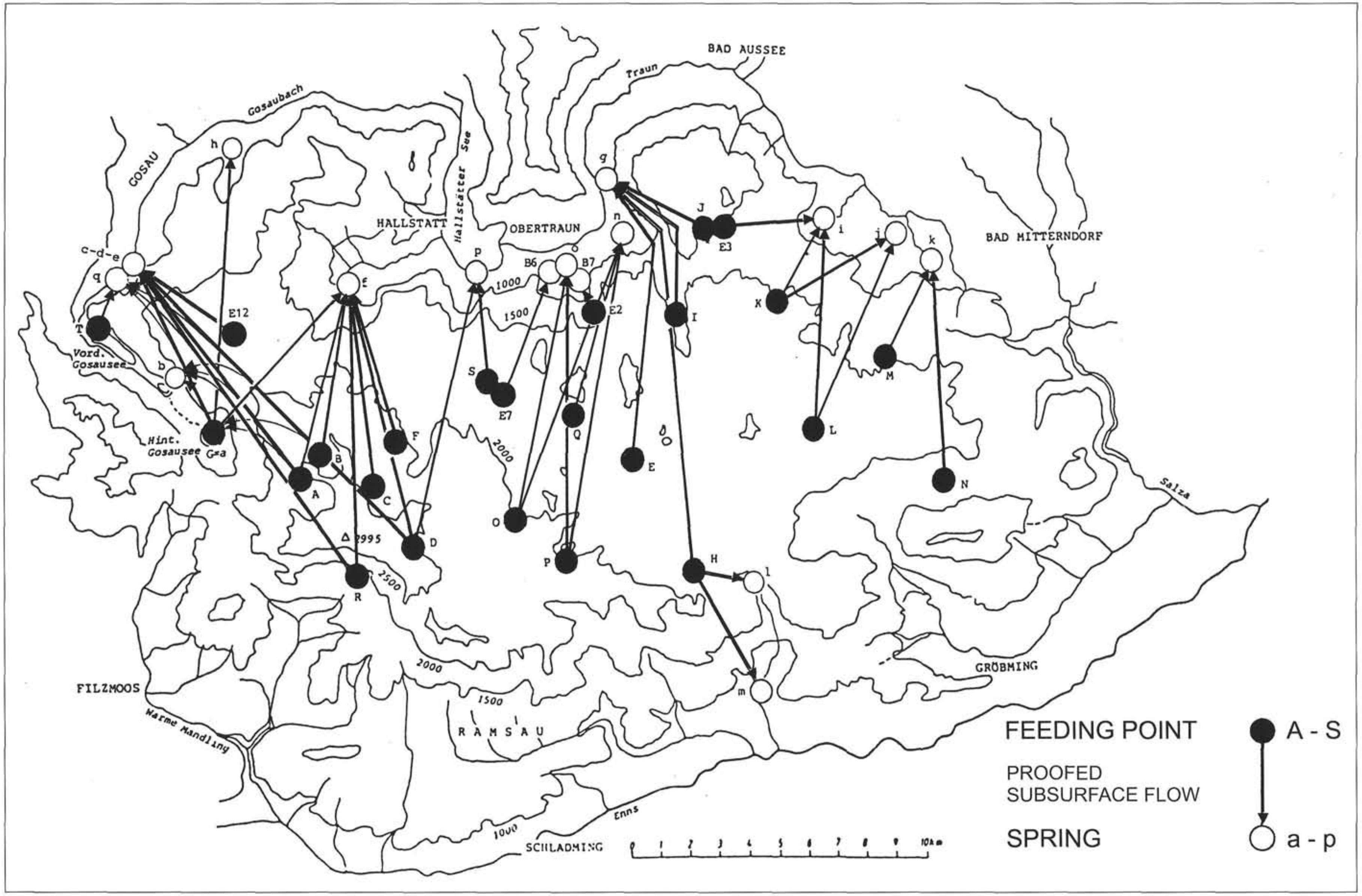


Fig. 7
Results of the fluorescence tracer tests in 1984, 1985, and 1986 (BAUER, 1989). Based on a critical evaluation, BAUER (1989) infers a predominantly northwards subsurface runoff of Dachstein massif, which is in contrast to MAURIN and ZÖTL (1959) (Fig. 6).

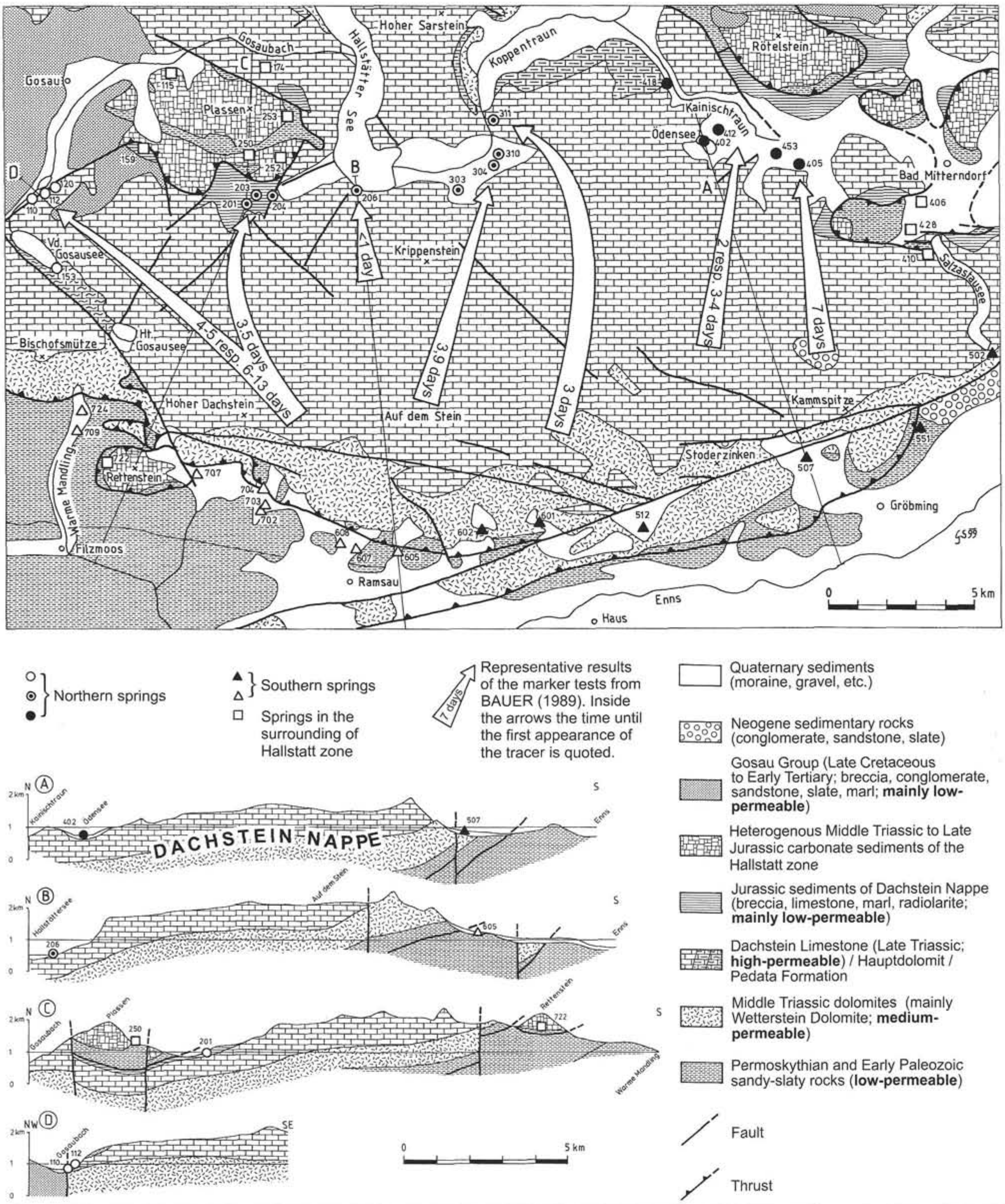
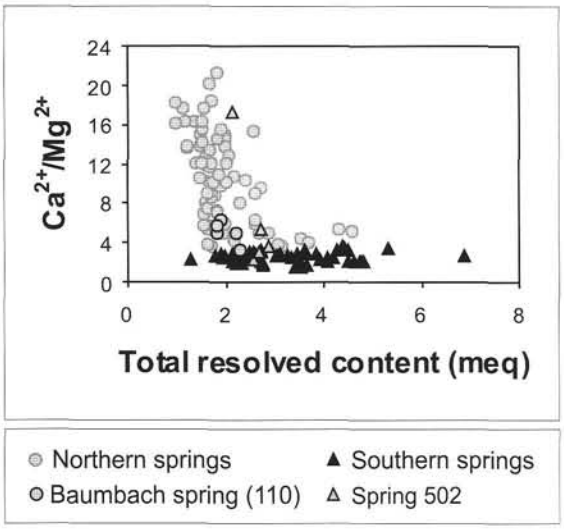
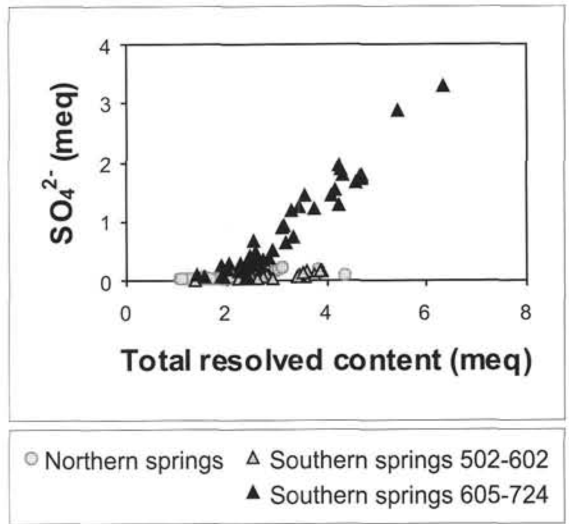


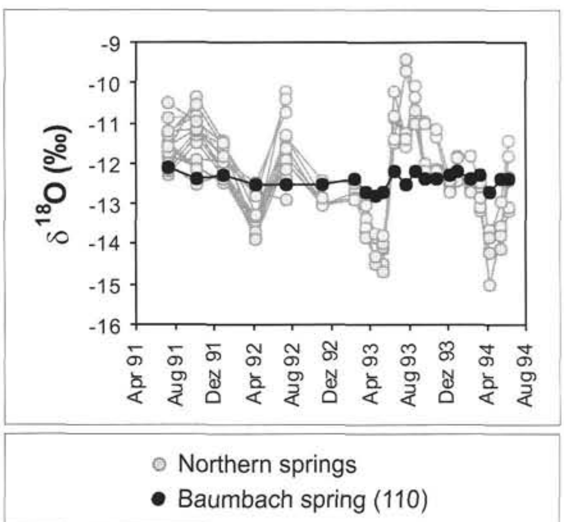
Fig. 8
Hydrogeological outline map and cross sections of Dachstein massif (SCHUBERT, 2000; geology after MANDL, 2000 and TOLLMANN, 1960).

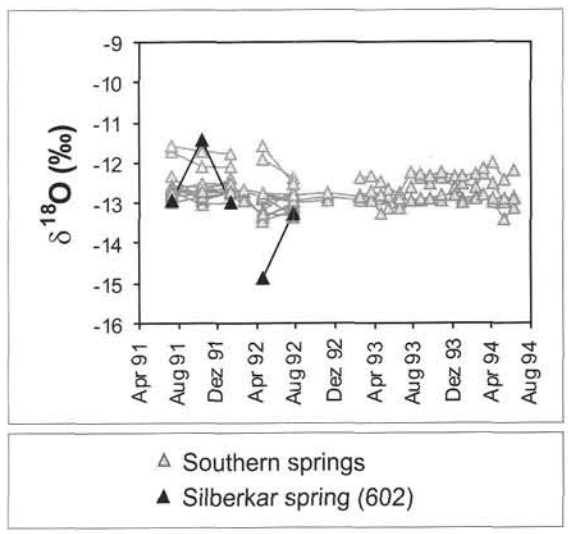
≤0.1 years) and 62 to 65% of an older one (mean residence time 3 years).

Baumbach spring, located in the southern Gosau valley (number 110 in Fig. 8), is an exception within the northern springs. Isotopic and chemical data suggest that this spring does not derive its discharge only from the Dachstein Limestone, but at a larg extent from the underlying Wetterstein Dolomite. The relatively constant $\delta^{18}O$-concentrations suggest that 7% of its runnoff has a mean residence time of 0.4 years, while 93% has a mean residence of 6 years. The Ca^{2+}/Mg^{2+}-ratios of the Baumbach spring lie between 3.3 and 6.3, whereas those of the other northern springs are









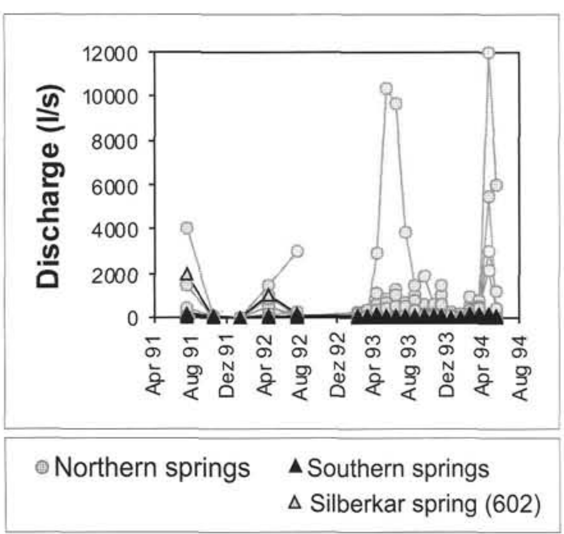


Fig. 9
Hydrographs and chemical discrimination diagrams of northern and southern springs. The northern springs represent a limestone type, whereas the southern springs are of a dolomite type.

mostly higher, namely between 3.6 to 23.3. Thus, the Baumbach springs looks like the southern springs described below.

As the mentioned fluorescence tracer tests show, the subsurface runoff of Dachstein massif goes generally in a northern direction. However, in the western Dachstein massif the subsurface runoff is split into the springs in the southern Gosau valley (number 112 etc. in Fig. 8) and into the spring district Waldbachursprung (number 201 etc.). This splitting is caused by the damming effect of the deep-drawing Permian and Early Triassic siliciclastic strata of the Hallstatt zone in the surroundings of Plassen (Fig. 8).

The southern springs of the Dachstein massif are dominated by a dolomite-rich recharge area. This finds its expression in the relatively low Ca^{2+}/Mg^{2+}-ratios and in the relatively low and constant outflows, as well as little varying $\delta^{18}O$-concentrations (Fig. 9). The Ca^{2+}/Mg^{2+}-ratios lie between 1.6 and 3.6 with the exception of spring 502, which rises on the contact Dachstein limestone to dolomite (Fig. 8). The relatively constant $\delta^{18}O$-concentrations suggest high residence times. The longer $\delta^{18}O$-hydrographs of the southern springs suggest an outflow composition of 3 to 14% of a younger component (mean residence time 0.2 to 0.4 years) and 86 to 94% of an older component (3 to 6 years). Springs with a dolomite-dominated recharge area are, as a rule, characterized by a balanced outflow and higher residence time, due to the high fracture porosity and storage capacity of dolomite.

Among the southern springs, the Silberkar spring (number 602 in Fig. 8) forms an exception concerning discharge and $\delta^{18}O$-variation. During the observation period its discharge varied between 20 and 2000 l/s, whereas the other southern springs had an outflow between 0.1 and 200 l/s. The highly-variable $\delta^{18}O$-concentrations of the Silberkar spring suggest a low residence time. However, this could not been quantified, because of its short observation period.

With regard to sulfate, the southern springs can be divided into a western group (number 605 to 724) with high SO_4^{2-}-concentrations and an eastern group (number 502 to 602) with low ones (Fig. 9). Whereas in the southwest of the Dachstein massif the groundwater of the dolomite sequence has contact with evaporites belonging to the aquifuge, this is not valid in the east.

The First and Second Vienna Water Lines

Vienna supplies its drinking water mostly from the Rax-Schneeberg and the Hochschwab regions 100 km southwest of Vienna (Figs. 1 and 10). These regions belong to the Northern Calcareous Alps and are characterized by particularly productive karst springs. According to statistics of the Vienna waterworks (HEBNAR, 1998), in the year 1997, the First Vienna Water Line supplied 56.69 million m^3 and the Second Vienna Water Line 81.46 million m^3 of water. This corresponds to an average runoff of 1800 l/s and 2600 l/s. In these amounts, a small part of pore groundwater is included.

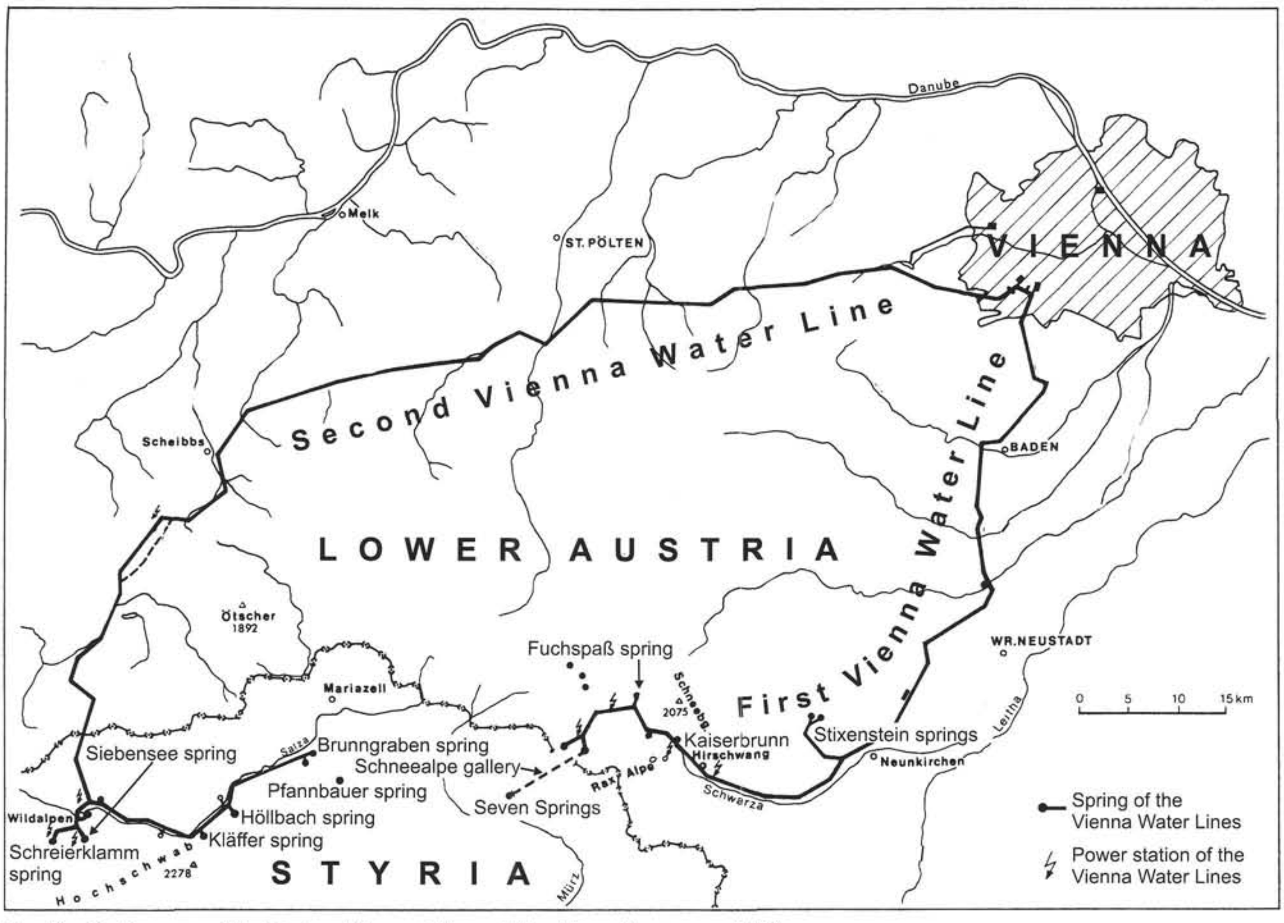
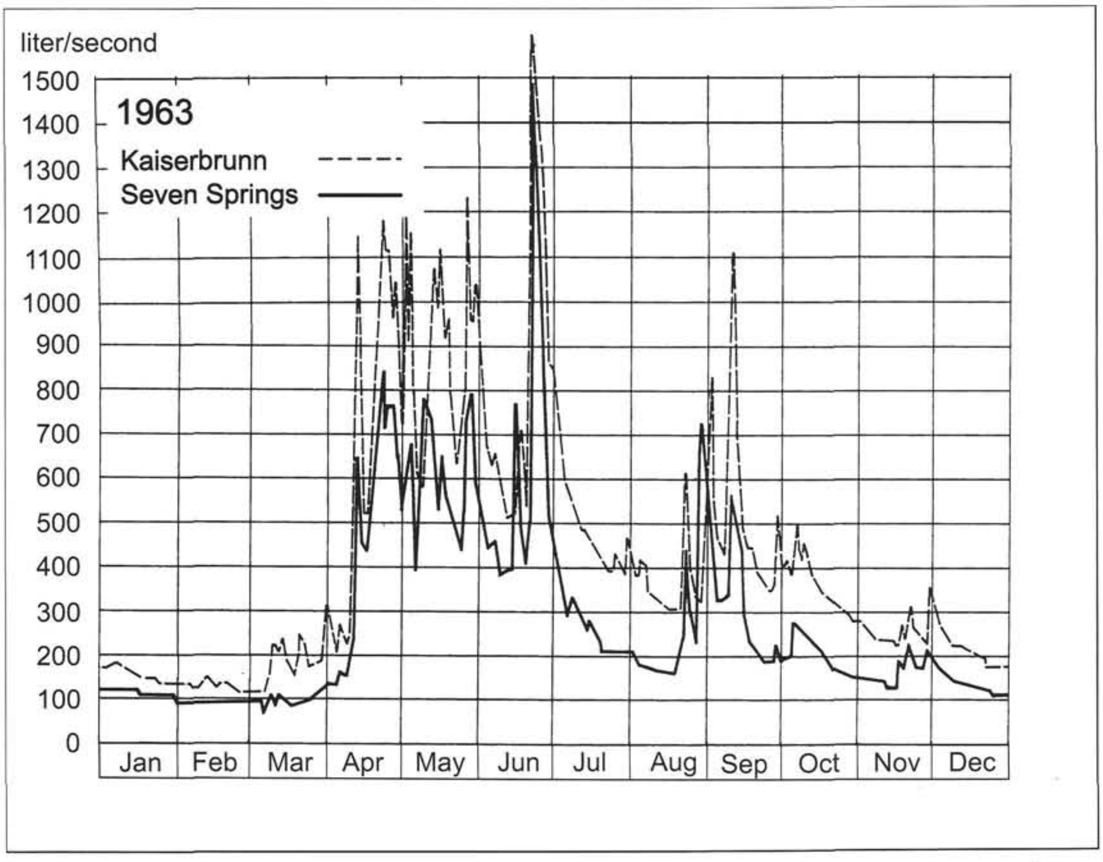


Fig. 10 Outline map of the First and Second Vienna Water Lines (GATTINGER, 1973).



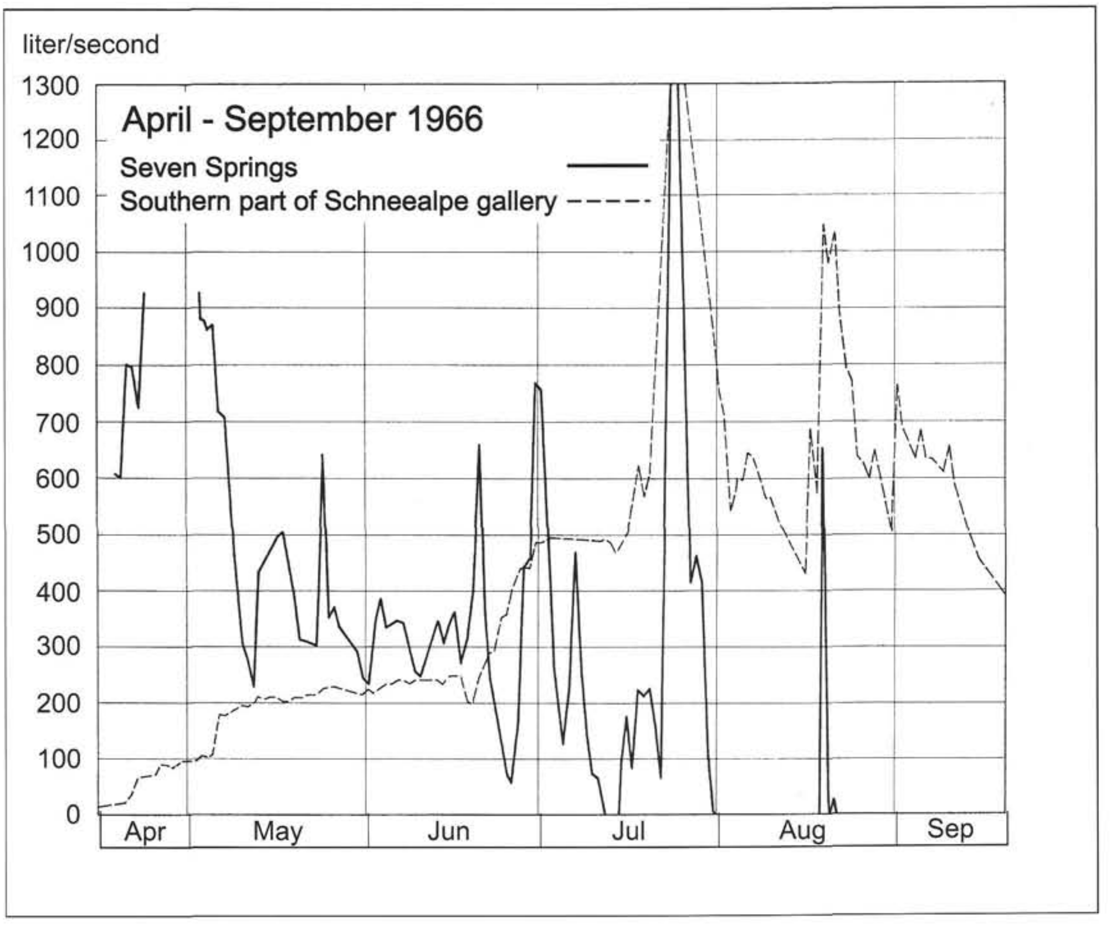


Fig. 11
Discharge hydrographs of Kaiserbrunn and Seven Springs in the year 1963 and of Seven Springs and the southern part of Schneealpe gallery during the water invasion in 1966 (DRENNIG, 1973).

First Vienna Water Line

The First Vienna Water Line was opened in 1873 upon the urging of EDUARD SUESS. Due to this water supply, the typhoid frequency in Vienna decreased considerably and cholera no longer occurred, except in single imported cases. At the beginning, only the water of the Kaiserbrunn (the most productive spring in the Rax-Schneeberg region) and the Stixenstein springs were used (Fig. 10). Due to increasing demand, continuously further springs and wells were captured. The most important activity in the process of expansion was the construction of the Schneealpe gallery in the sixties (DRENNIG, 1973). The 8600 m long gallery was built in order to add the water of the Seven Springs to the First Vienna Water Line, from the catchment area of the Mürz river to the catchment area of the Schwarza river (Fig. 10). The Kaiserbrunn and the Seven Springs are typical karst springs with strongly varying discharges (Fig. 11).

The geological situation in the environment of the Schneealpe gallery is as follows (GATTINGER, 1973): Above an impermeable base with mainly slaty-siliciclastic strata of the Graywacke zone (Early Paleozoic) and Werfen Formation (Early Triassic) a thick permeable Middle Triassic carbonate sequence follows, build up by Gutenstein Limestone/Dolomite as well as Wetterstein Limestone/Dolomite (Fig. 12). Within the impermeable base, Permian evaporites with gypsum and anhydrite (Haselgebirge) were found.

The construction of the Schneealpe gallery started in 1965. With progressive tunneling in the southern part of the gallery, in the surroundings of Seven Springs there were repeatedly extensive water inrushes. In the course of these water invasions, the outflow of the southern part of the gallery increased while the discharge of Seven Springs decreased (Fig. 11). On 12th July, 1966, Seven Springs became dry, at which the discharge of the southern part of the gallery amounted to 500 l/s. Initially, the aim of the Schneealpe gallery project had been to make a surface capture of Seven Springs and transfuse their water into the Schneealpe gallery by pipes. However, because the water of Seven Springs infiltrated directly into the gallery, the pipe transfusion became unnecessary. Later, the gallery was walled up and equipped with gate valves to regulate the discharge of the gallery and the Seven Springs. The Vienna waterworks got the permission to capture 400 l/s from the Schneealpe gallery (DRENNIG, 1973).

The Rax-Schneeberg region is not only used by the First Vienna Water Line, but also developed for tourism. For example, there exist a rack-railway on Schneeberg and a cable railway on Rax. To get facts about the vulnerability of the Schneeberg region, DOSCH (1956a, b) carried out a fluorescence tracer test in 1955 (Fig. 13). On Hochschneeberg, 9.5 kg uranin were exposed into a swallow hole at ca. 1800 m altitude. Among others, the tracer could be found in Kaiserbrunn (3.6 km remote the from swallow hole, 1279 m above see level) and Fuchspaß spring (6.4 km remote from swallow hole, 1223 m above see level) 16 hours later, as well as in Stixenstein springs (12.5 km remote from swallow hole, 1320 m above see level) 2 days later. Kaiserbrunn was affected heavily, in Kaiserbrunn 89% of the recovered tracer discharged (the recovery-rate amounted 61%).

Second Vienna Water Line

The Second Vienna Water Line started to operate in 1910. It obtains water from the Hochschwab region (Fig. 10). At the date of opening, only the Kläffer spring (the most productive spring in

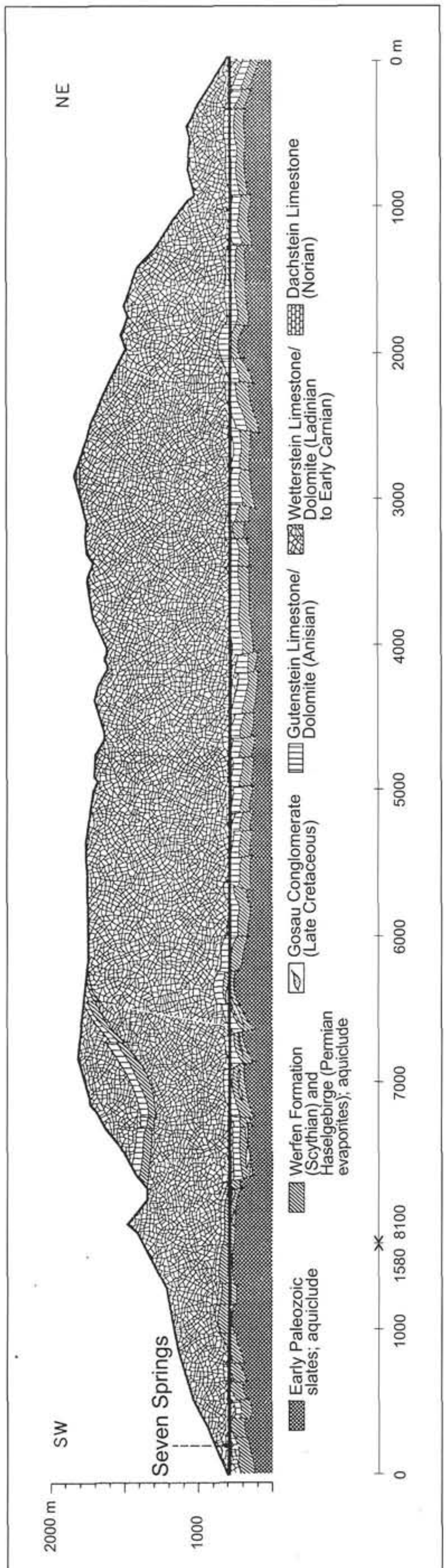


Fig. 12
Geologic section of Schneealpe gallery (DRENNIG, 1973). For location, see Fig. 10.

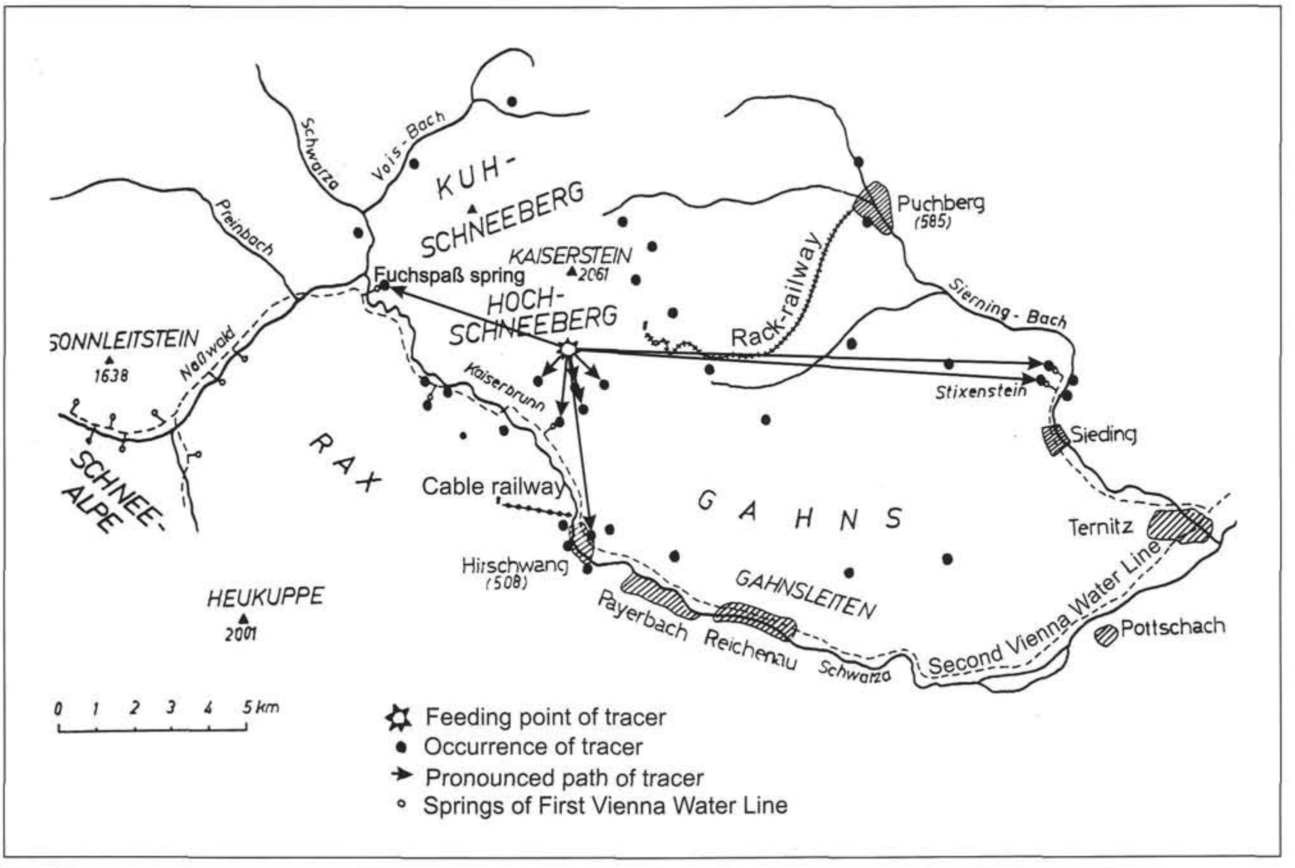


Fig. 13
Results of the fluorescence tracer test of DOSCH (1956a, b) in the Rax-Schneeberg region (MAURIN and ZÖTL, 1959).

the Hochschwab region), the Siebensee spring and the Schreierklamm spring were captured. Due to the increasing demand, also in the surroundings of the Second Vienna Water Line, further springs have been caught (DRENNIG, 1988).

In the course of a detailed spring mapping in the Hochschwab region, ZÖTL (1961) worked out significant differences between springs with calcareous recharge areas and springs with inflow areas mainly consisting of dolomite – namely by total hardness and discharge characteristics. The total hardness of limestone springs always lay beneath 7°dH. Between 8.5 and 10.5°dH, dolomite springs were predominant. Even more evident differences were shown by discharge. For example, in the year 1955, the Kläffer spring as a typical limestone variety had a strong varying discharge (between 800 and 9800 l/s), whereas the Brunngraben spring, as a typical dolomite type, has shown low discharge fluctuations (between 240 and 460 l/s).

In 1971, in the Hochschwab region, a tracer test was carried out by BAUER (1972). The tracer (uranin and sulforhodamin) was fed into the underground in the Aflenzer Staritzen, 10 km east of the Kläffer spring (Fig. 14). The tracers were only evident in the Kläffer spring, whereas in the Höllbach spring and the other springs in the surroundings no tracer was found. From this circumstance, it could be concluded that the Aflenzer Staritzen are predominantly discharged by the Kläffer spring. This corresponds to the geological structure (Fig. 14): In the north of Aflenzer Staritzen, there are W-E orientated faults which are accompanied by Early Triassic shale. The shale forms an aquiclude in combination with the fault gouge zones. In the valley of Hintere Höll, the shale is not outcropping, but according to stratigraphy, it can be assumed to be present in the underground (pers. comm. Mr. BRYDA). To the east and the south of Aflenzer Staritzen, Early Triassic and also Permian siliciclastic sedimentary rocks form an aquiclude. As a consequence, it can be expected that the groundwater of Aflenzer Staritzen discharges mostly to the Kläffer spring in the west.

The northeastern part of the Hochschwab region is currently being remapped in detail by the Geological Survey in Vienna (BRYDA et al., 1999). Furthermore, in this region, the Joanneum Research in Graz (STADLER and STROBL, 1997) carried out extensive hydrogeological investigations concerning discharge characteristics and recharge area. In the Zeller Staritzen, STADLER and STROBL (1997) distinguished an eastern spring type with a dolomitic recharge area from a western type with a calcareous one by modern methods. In the east, Zeller Staritzen consists mainly of the Middle Triassic Wetterstein Dolomite, whereas in the western part the Middle Triassic Wetterstein Limestone dominates (Fig. 14). The eastern type is represented by the Pfannbauer and the Brunngraben springs and is characterized by low Ca^{2+}/Mg^{2+}-ratios, low varying outflows and high mean residence time. The Höllbach spring is a representative of the western type; it shows a high Ca^{2+}/Mg^{2+}-ratio, high varying discharge and low mean residence time (Table 1).

In this study, a water balance calculation, as well as isotope hydrological and hydrochemical equilibrium calculations, were made to infer the recharge areas of the

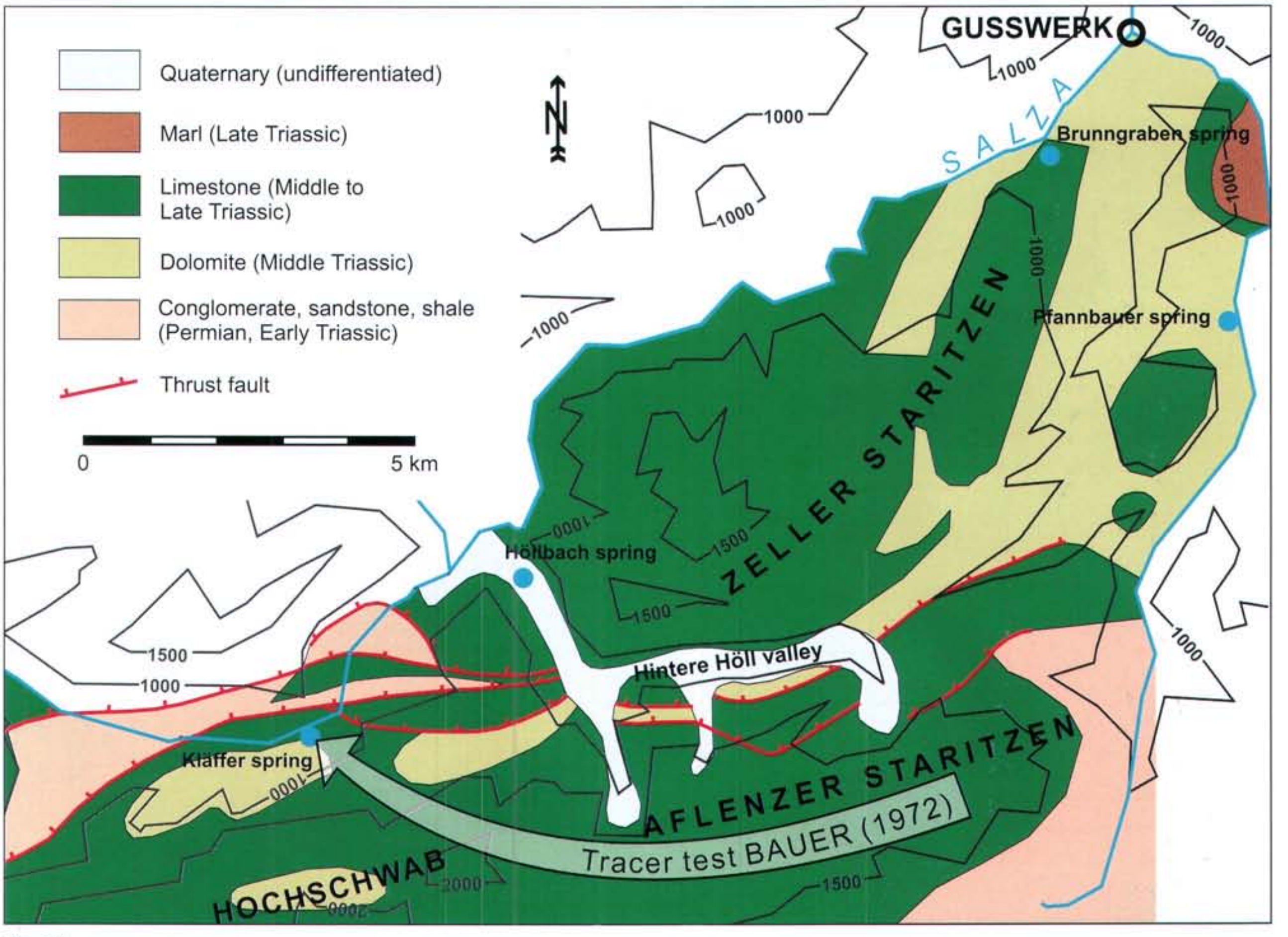


Fig. 14
Hydrogeological outline map of Zeller and Aflenzer Staritzen. The Geology is strongly simplified according to BRYDA et al. (1999). The arrow display the result of the fluorescence tracer test of BAUER (1972).

springs. Mainly the water balance calculations indicate that the recharge area of the Höllbach spring includes not only the Zeller Staritzen, but also the northern part of the Aflenzer Staritzen (Fig. 14). This seems to be in contrast to the results of the fluorescence tracer test of BAUER (1972) mentioned before. From the tracer test it can be inferred that Aflenzer Staritzen are discharged by the Kläffer spring. It seems that depending on the groundwater table, groundwater occasionally flows over the geological barrier in the underground of the Hintere Höll valley (pers. comm. Mr. STROBL).

Mitterndorf Depression

The Mitterndorf depression is situated in the southern Vienna basin (Fig. 1). It represents the most important pore aquifer in Austria. It is filled by thick Quaternary gravel and Pliocene conglomerate, which together reach a thickness of about 150 m. Between Neunkirchen in the SW and Schwadorf in the NE it covers a length of 50 km and a width of 3 to 12 km (Fig. 15). Because of dense settlement and industrialisation, the groundwater of the Mitterndorfer depression is exposed to a high risk of contamination.

Table 1
Data of selected eastern type springs (Pfannbauer and Brunngraben springs) and a representative western type spring (Höllbach spring) of Hochschwab region (STADLER and STROBL, 1997). The Ca^{2+}/Mg^{2+}-ratio relates to eq. qmin is the minimal and qmax the maximal discharge observed.

	Ca^{2+}/Mg^{2+}-ratio	q_{max}/q_{min}	Mean residence time (^3H-exponential model)
Pfannbauer spring	1.6-2.4	1.4	21.5 a
Brunngraben spring (chamber A)	2.8-3.8	1.5	10.5 a
Höllbach spring (main capture)	3.0-5.2	4.1	6.0 a

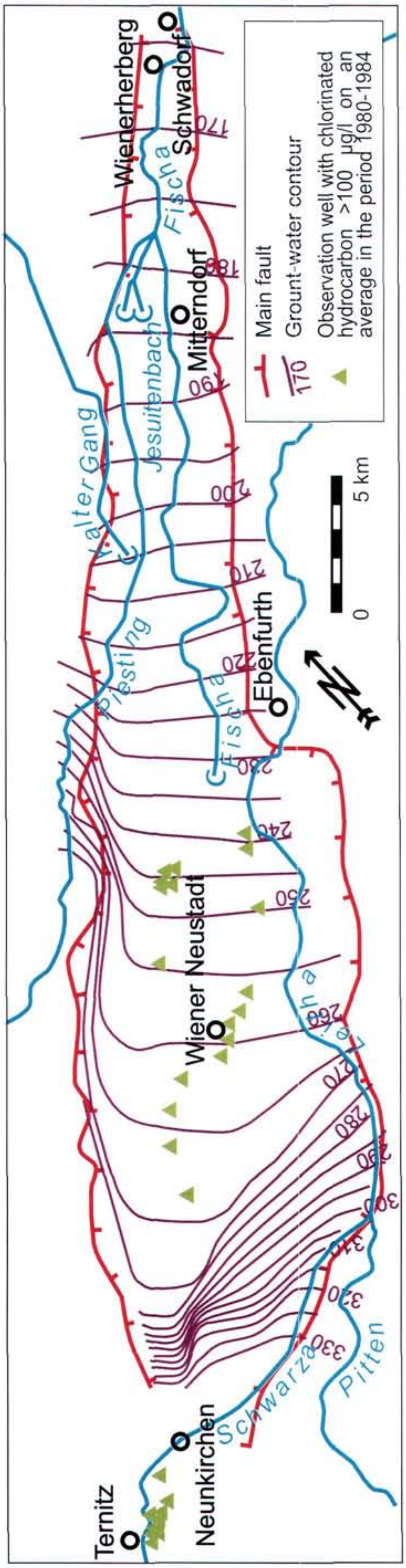


Fig. 15
Groundwater contours of Mitterndorf depression after BERGER (1989) and FORSCHUNGSZENTRUM SEIBERSDORF (1992).

The full hydrogeological context of the Mitterndorf depression was first realized by KÜPPER (1954). From the low precipitation in the southern Vienna basin, he inferred that the groundwater of the Mitterndorf depression is mostly recharged by groundwater inflow and infiltrating river water. By means of systematic water temperature observations, he found those springs and river sections in the northeastern part of the depression which discharge it. Based on numerous hydrochemical analyses, KÜPPER (1954) distinguished the relatively well-mixed, uniform groundwater in the central part of the depression from local groundwater types in marginal regions influenced by local intake areas.

A reinvestigation of the Mitterndorf depression was carried out by BERGER (1989). He evaluated numerous drilling and geoelectric profiles and worked out the tectonic and hydrogeological situation in detail. BERGER (1989) distinguished two tectonic units: the sector Ebenfurth-Wienerherberg in the NE and the sector Ebenfurth-Neunkirchen in the SW (Fig. 15). The sector Ebenfurth-Wienerherberg is clearly bordered by marginal faults with considerable vertical displacement. Furthermore, this segment is scarcely sectionalized. In spite of this, the sector Ebenfurth-Neunkirchen is subdivided into numerous horsts and grabens.

BERGER (1989) considered not only the Quaternary gravel but also the Pliocene Rohrbach Conglomerate as storage-relevant sediment. The Rohrbach Conglomerate is the substratum of Quaternary gravel in the southwestern part of the depression. The aquiclude of the Mitterndorf depression is mostly built by fine-grained Neogene sediments. With regard to the hydrogeological function, BERGER (1989) subdivided the Mitterndorf depression into the sections Neunkirchen-Wiener Neustadt, Wiener Neustadt-Ebenfurth, and Ebenfurth-Wienerherberg/Schwadorf (Fig. 15). The recharge of the Mitterndorf depression takes place mainly in the southwest, in the sector Neunkirchen-Wiener Neustadt. Waterfall-like inflow of groundwater out of the thin gravel of the surroundings and oozing surface water from the rivers Schwarza and Leitha replenish the aquifer here.

Within the middle sector (Wiener Neustadt-Ebenfurth), only little autonomous recharge occurs. An example is the infiltration of river water from the Piesting. On the other hand, in the course of a high groundwater table caused by abundant groundwater inflow, in the middle sector groundwater discharges into the Leitha river.

The sector Ebenfurth-Wienerherberg/Schwadorf in the northeast represents the main groundwater storage of the Mitterndorf depression. Practically no recharge happens here, but the Mitterndorf depression is discharged by productive springs and groundwater extrusions into the rivers. Examples are the springs of the rivers Kalter Gang and Jesuitenbach (Fig. 15). According to BERGER (1989), the total groundwater circulation of the Mitterndorf depression amounts on an average to about 4 to 6 m^3/s.

In the early eighties, it became obvious that the groundwater of the Mitterndorf depression is considerably contaminated by chlorinated hydrocarbons (BERGER, 1989). An industrial site in Ternitz (near Neunkirchen) could be located as the main source contaminating the whole central channel, due to its position at the beginning of the groundwater stream of the Mitterndorf depression (Fig. 15). The diverse further contamination centers located downstream were characterized by rather local contaminant plumes. As a consequence, well fields situated within the central groundwater stream were predominantly contaminated.

A further considerable source of chlorinated hydrocarbon pollution is the so-called Fischer depository situated 4 km north of Wiener Neustadt (FEDERAL ENVIRONMENT AGENCY, www.ubavie.gv.at). This depository was used from 1972 to 1987, and has a volume of about 800,000 m^3. Today, downstream from the depository, the contaminated groundwater is captured by wells and cleaned by activated carbon filter.

cal data indicate a recharge area reaching further northward than deduced by HEISSEL (1993).

The phenomenon that the recharge area estimated by water balance is larger than that based on geology, occurs also in other regions of the Northern Calcareous Alps. There are two possible reasons for this effect: The first results from the difficulties in measuring representative precipitation heights in Alpine regions. The second is the fact that geological barriers are not completely tight.

According to RAMSPACHER et al. (1992), from the relatively low $\delta^{18}O$-fluctuations (Fig. 5), i. e. the damping of the input signal, which is given by precipitation, the mean residence time of Mühlau springs amounts more than 6 years. By way of the exponential model, the Tritium-contents show that the waters from the Wurmbach and Klammbach galleries (8 to 10 years) are younger than those of the Rum gallery (11 to 15 years). The Rum gallery captures a somewhat deeper, and therefore older, groundwater. Based on an average mean residence time of about 12 years and on a mean total discharge of 1370 l/s, RAMSPACHER et al. (1992) estimated a storage volume of the aquifer of the Mühlau springs of about 516 million cubic meters. Under the assumption of an aquifer thickness between 300 and 500 m, they further deduced a porosity of about 3 to 5%.

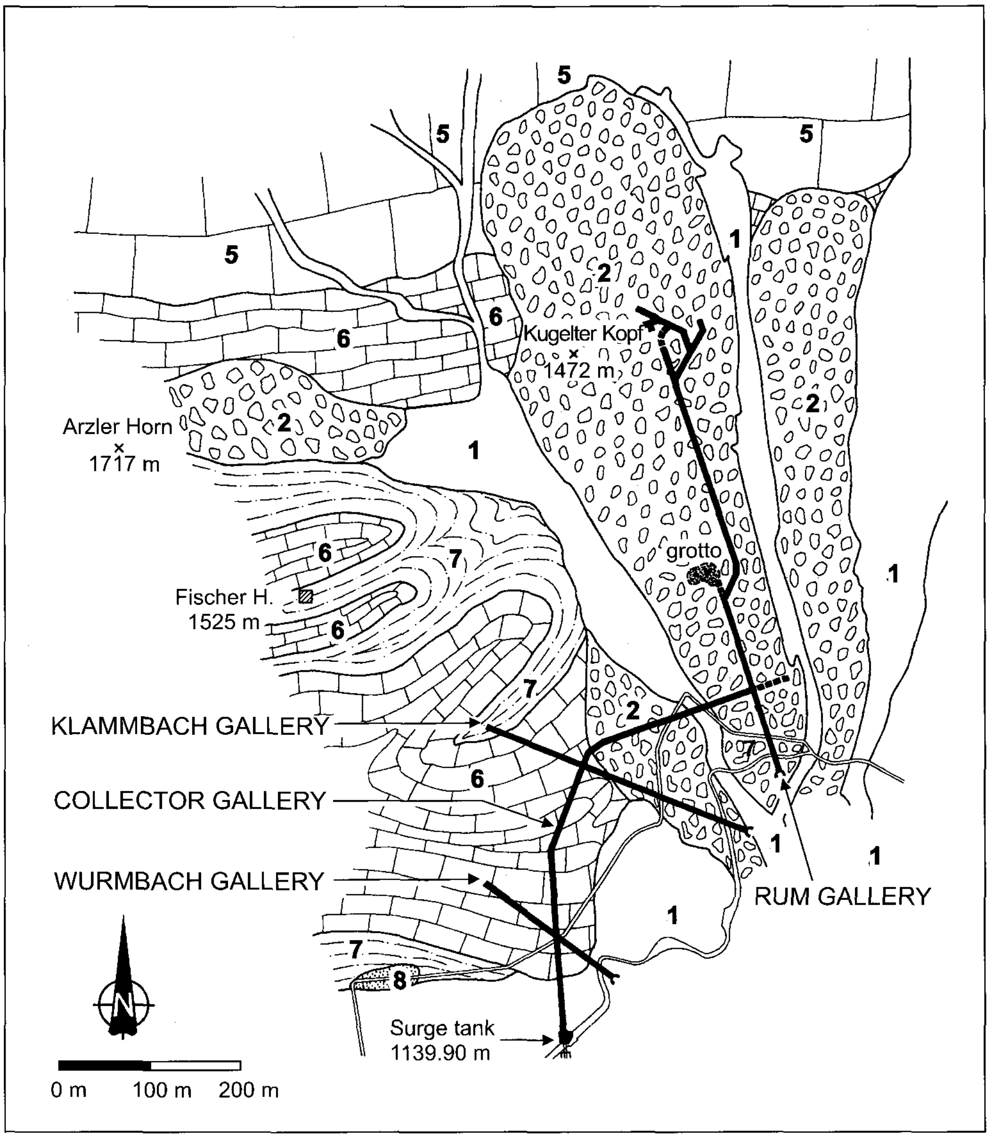


Fig. 3
Geological sketch of the environment of Mühlau springs (HEISSEL, 1993). For legend, see Fig. 4.

Dachstein Massif

The Dachstein massif (Fig. 1) represents one of the largest karst plateaus in Austria. It covers an area of 40 km in length by 20 km in width and reaches an altitude of 2995 m above sea level. The Dachstein massif consists of a thick northward dipping Triassic carbonate sequence. This region, the site of the prehistoric salt mine of Hallstatt belongs to the World Heritage of UNESCO.

The Dachstein massif has been extensively explored by tracer tests. These investigations have been an important contribution to the progress of tracer techniques. This concerns both *Lycopodium* spores tracers and fluorescence tracers. In the Dachstein region *Lycopodium* spores were used even in 1953, by MAYR (1956). He marked a swallow hole on the shore of the lake Hinterer Gosausee (point F2 in Fig. 6) and found out connections to the karst spring Waldbachursprung (point E1) in the northeast and to the karst springs in the southern Gosau valley (point F4) in the northwest. In times of a high groundwater level this swallow hole acts as spring.

Due to a new method of dying *Lycopodium* spores in different colors (DECHANT, 1959), it became possible to apply *Lycopodium* spores simultaneously to several places within one area. In 1956 and 1958, spacious spore tracer investigations were carried out in the whole Dachstein massif (MAURIN and ZÖTL, 1959). The results of these tracer tests

Fig. 4 →
Geological cross sections of Wurmbach, Klammbach, and Rum galleries (HEISSEL, 1993). For location, see Fig. 3.