Karst hydrogeology and origin of thermal waters in the Codru Moma Mountains, Romania

Iancu Oraseanu · John Mather

Abstract Two karst areas within Permian and Triassic carbonate rocks of the Codru Moma Mountains in the northwestern part of Romania yield thermal waters. Major karst springs occur where groundwater flow is intercepted by hydraulic barriers, which also results in the movement of water from deeper levels. At Moneasa, thermal groundwater rises along faults and fractures associated with a thrust, and at Vascau Town, water rises along faults marginal to the Beius Basin. Geochemistry suggests that the thermal component of the Moneasa groundwaters is derived from dolomites and that at least a proportion of the Vascau thermal waters originates from deeply buried Permian sandstones.

Résumé Deux régions karstiques développées dans les roches carbonatées du Permien et du Trias des Monts Codru Moma, dans le nord-ouest de la Roumanie, possèdent des sources thermales. Les principales sources karstiques apparaissent là où les écoulements souterrains recoupent des barrières hydrauliques, qui provoquent aussi la remontée d'eaux depuis des niveaux plus profonds. Á Moneasa, les eaux thermominérales remontent le long de failles et de fractures associées à un chevauchement; dans la ville de Vascau, l'eau émerge le long des failles de la marge du bassin de Beius. La géochimie laisse penser que la composante thermale des eaux souterraines de Moneasa provient des dolomies et qu'au moins une partie des eaux thermales de Vascau provient des grès permiens enfouis profondément.

Resumen En las Montañas Codru Moma, al Noroeste de Rumanía, hay dos áreas kársticas desarrolladas en rocas carbonatadas del Pérmico y Triásico donde se obtienen aguas termales. Los manantiales kársticos más importantes se originan en los puntos de intersección del flujo subterráneo con barreras hidráulicas, hecho que facilita el desplazamiento del agua desde niveles inferiores. En Moneasa, las aguas subterráneas termales ascienden a través de fallas y fracturas asociadas a mantos de corrimiento (*thrusts*, por aplicación de cargas superficiales) y, en la ciudad de Vascau, a través de fallas marginales de la cuenca Beius. La geoquímica indica que la componente termal de las aguas subterráneas en Moneasa procede de dolomitas, mientras que al menos una parte de las aguas subterráneas en Vascau procede de areniscas muy profundas del Pérmico.

Key words karst · groundwater flow · thermal conditions · Romania

Introduction

Geologic Setting

In the Apuseni Mountains, western Romania, carbonate rocks crop out over large areas and occur within all the main tectonic units. The Codru Moma Mountains are west of the main Apuseni block and are separated into a discrete mountain range by the Crisul Negru River to the east and the Crisul Alb River to the west. Locations are shown in *Figure 1.*

Structurally, the Codru Moma Mountains form part of the Codru Nappe system from the Northern Apuseni Mountains. This system has a crystalline basement overlain by a thick succession of molasse deposits of Upper Permian/Lower Triassic age, which in turn are overlain by Triassic rocks that are predominantly carbonates. After a short period of emergence in the middle part of the Jurassic Period, the Codru area was submerged for the final time during Late Jurassic/Early Cretaceous time and was later thrust into a series of nappes (Bleahu et al. 1981).

During the Miocene Epoch, widespread extension, which affected the Carpathians, divided the Apuseni Mountains. The fallen blocks were invaded by the Pannonian Sea, forming the future Tertiary basins of Vad, Beius, and Zarand (*Figure 1*). The uplifted

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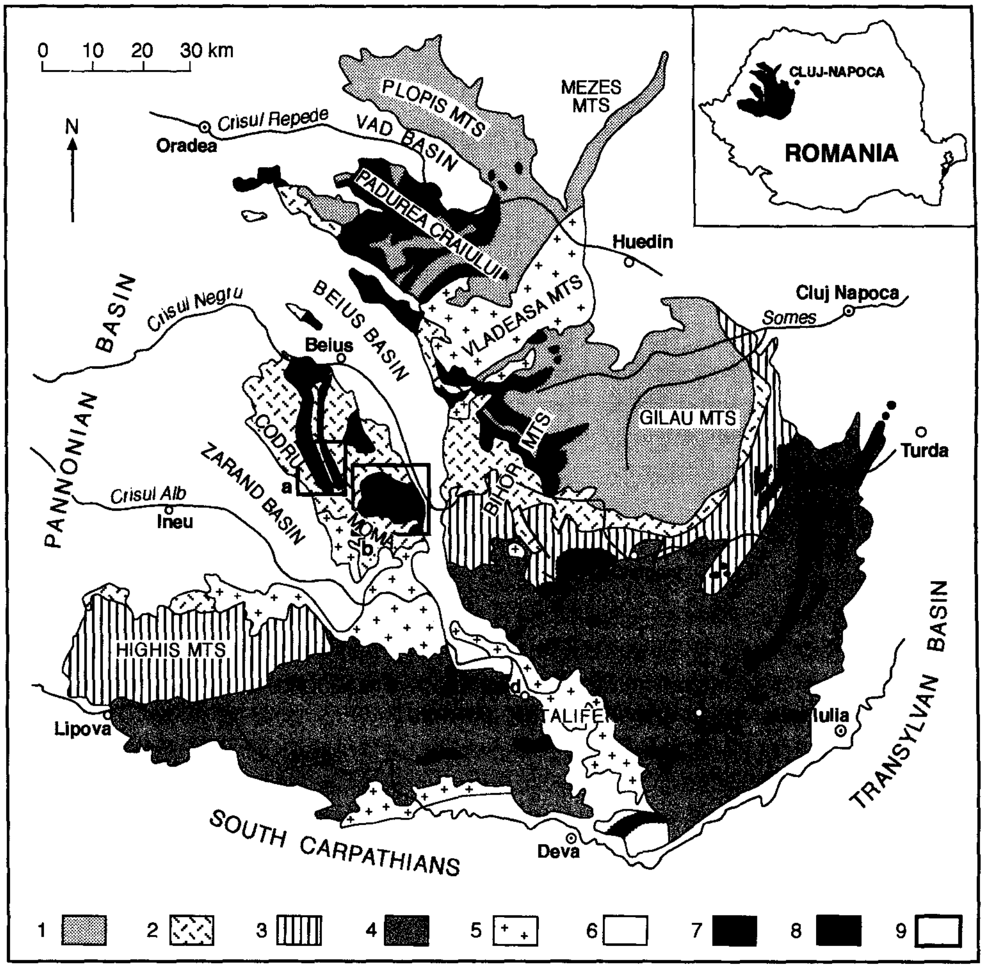


Figure 1 Distribution of karst terrains in the Apuseni Mountains (after Oraseanu 1994). *1* Bihor Autochton; *2* Codru Nappe System; *3* Biharia Nappe System; *4* Southern Apuseni Mountains (Nappe System and Ophiolites); *5* Upper Cretaceous and Tertiary magmatic rocks; *6* Tertiary deposits; *7* sedimentary limestones and dolomites; *8* metamorphosed limestones and dolomites; *9* location of study areas: *a* Moneasa, *b* Vascau Plateau

blocks acted as islands during this period, and one of these islands now forms the Codru Moma Mountains.

Objectives

This paper is concerned with two karst areas within the Codru Moma Mountains. The Moneasa area lies in the west-central part and the Vascau Plateau in the southern part of the mountains (*Figure 1*). Both areas have been the subject of studies by Romanian hydrogeologists (Oraseanu 1985, 1987) because of the interest in their thermal waters and their tourist potential. However, the literature is in Romanian journals and not readily accessible to the international hydrogeological community. The objective of the present paper is to review the available data and more recent hydrogeochemical work, and to identify the origins of the thermal groundwaters.

Moneasa Area

Background

The Moneasa area is well known for its thermal waters, which are exploited through four springs and three wells and which attain temperatures of 24–32.8 °C. The presence of the Moneasa River, a tributary of the Crisul Alb River, and its situation in an area of diverse scenery, resulting from the complex geological structure, make Moneasa an extremely attractive spa town. The structural geology and hydrogeology of the Moneasa area are shown in *Figure 2* and a more detailed map of Moneasa spa itself in *Figure 3*. The topography of the area is dominated by the Izoi summit at 1098 m (*Figure 2*). From here the elevation decreases by more than 400 m to the east into the depressions of Brãtcoaia and Tinoasa-Izoi, with a further decline to the valley of the Meghes River, which has an average elevation of about 350 m above mean sea level.

The surface waters are collected by the Moneasa River, whose valley closely follows the line of the thrust plane along which the rocks of the Moma Nappe to the south are thrust over the Finis Nappe to the north (*Figure 2*). Relationships are shown in the geologic section of *Figure 4*. The supply to the stream is asymmetrical, with tributaries derived from the karstic limestones entering only from the north. The Moneasa area has a continental climate with Mediterranean influences; the mean annual precipitation is 1122.6 mm and the mean annual temperature 9.5 °C.

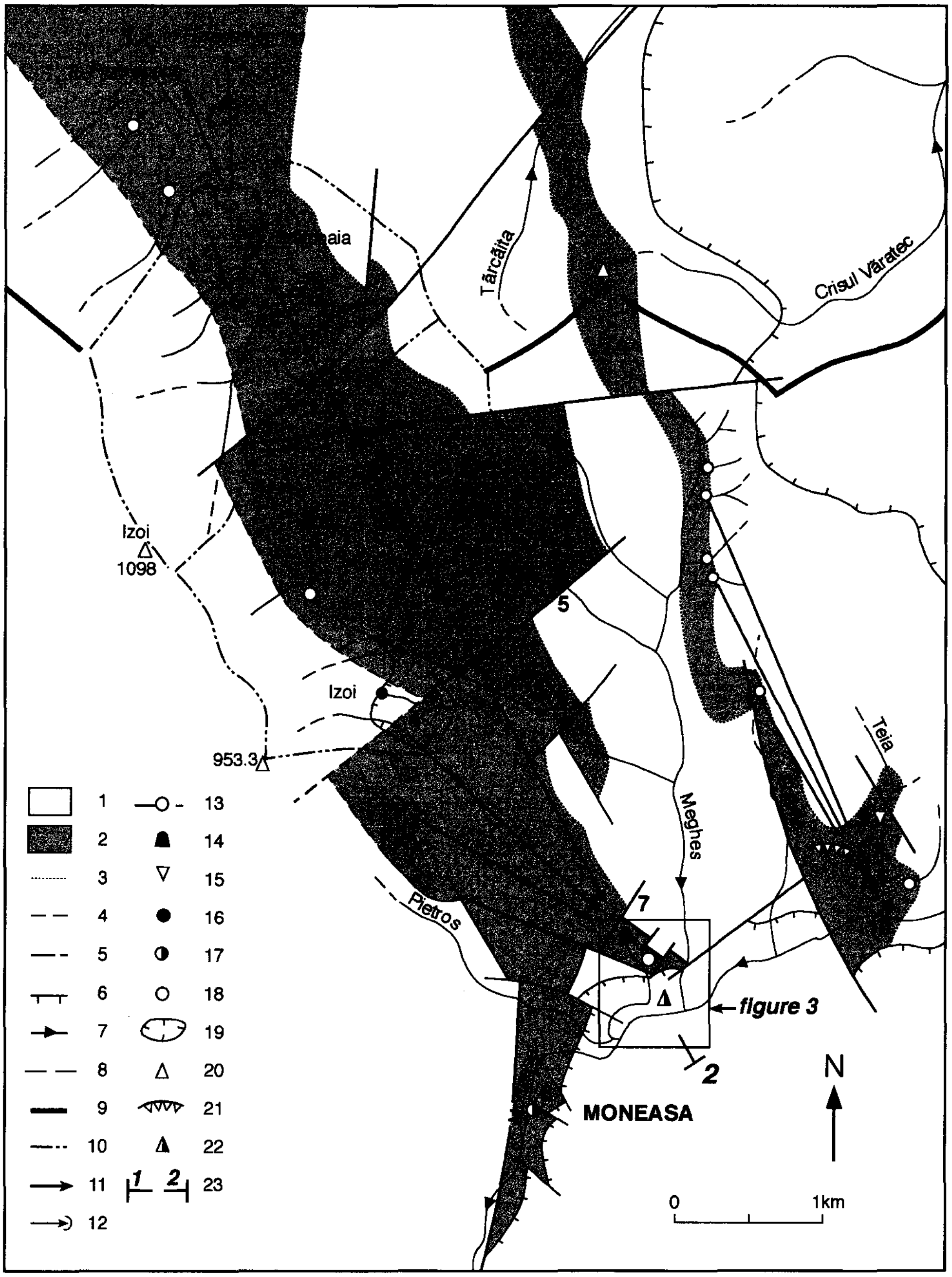


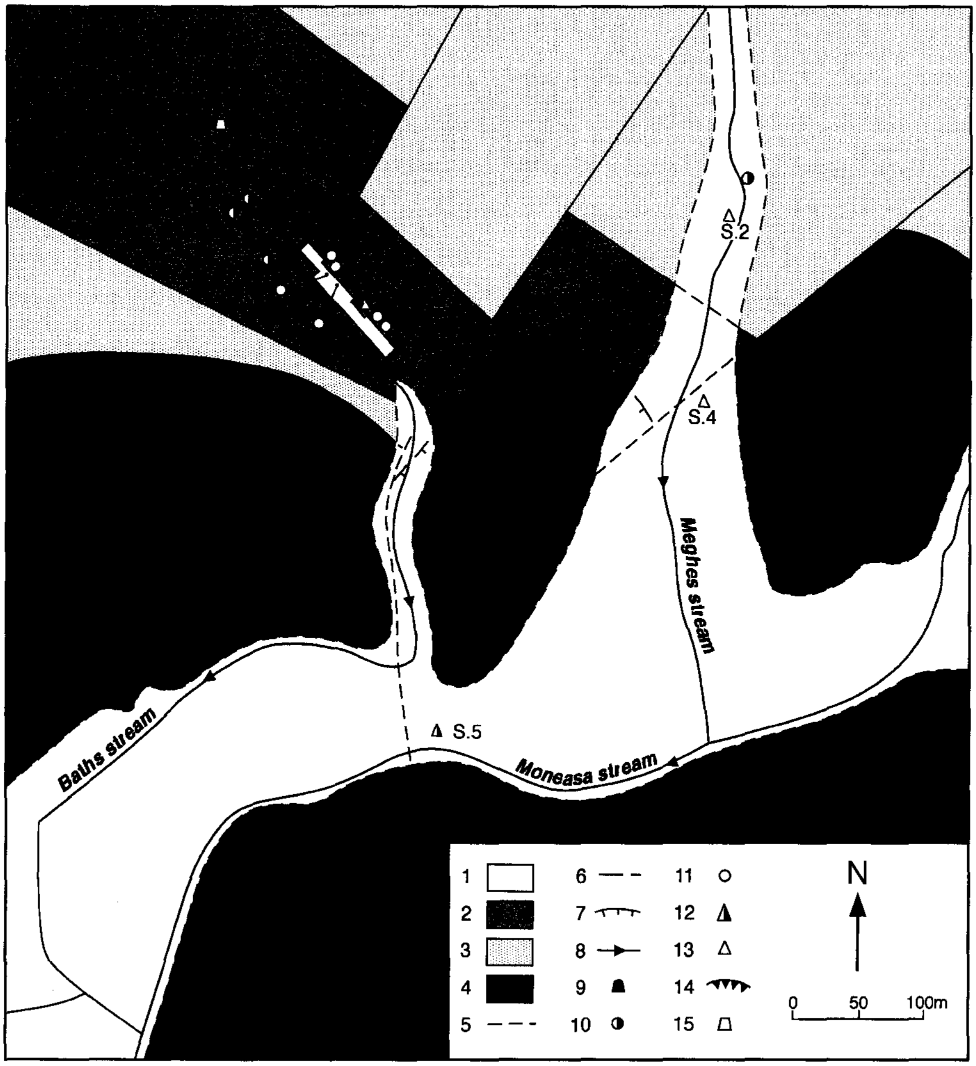
Figure 2 Hydrogeological map of Moneasa area (after Oraseanu 1987). *1* Non-carbonate terrains; *2* carbonate terrains; *3* boundary between rock formations; *4* boundary beneath drift; *5* fault; *6* thrust front (*symbol* on hanging side); *7* course of perennial stream (*arrow* indicates direction of flow); *8* course of intermittent stream; *9* surface-water divide between drainage basins of the Crisul Negru and Crisul Alb Rivers; *10* limit of internally drained areas; *11* proven underground hydraulic connection between surface sink and resurgence; *12* sink; *13* losses in streambed; *14* perennial resurgence cave; *15* perennial insurgence pothole; *16* spring with cold water; *17* spring with hypothermal water (10–20 °C); *18* group of springs with mesothermal water (21–36 °C); *19* karstic depression; *20* summit (elevation above sea level in metres); *21* quarry; *22* well with thermal water; *23* position of hydrogeological cross section (see *Figure 4*)

The karst is characterised by numerous caves and potholes, the most notable being Bear's Cave and Teia pothole. Bear's Cave (site 7 in *Figure 2*) is 250 m long and was discovered in 1984 at the end of a 20-m-long siphon from the resurgence that forms the Bear's Cave Spring. The Teia pothole (site 9 in *Figure 2*) is close to a quarry that exploited red limestone breccias. It is 1337.5 m in length with a 90-m difference in level over its length.

From a geological viewpoint, the Moneasa spa area is situated along the contact where the Permian volcanics and sediments of the Moma Nappe are thrust over the Finis Nappe. The sediments of the Finis Nappe form a monocline that trends approximately north/south with an eastward slope. The Nappe is built up with Lower-Triassic (Werfenian) quartzitic sandstones at the base, overlain by two carbonate sequences that are separated by a thick marly shale of Late Triassic age. The lower carbonate sequence, of Middle Triassic age, includes black dolomites and limestones with chert and white dolomites and violet brecciated limestones. The upper sequence consists of Lower Jurassic black and red limestones.

The rocks of the Finis Nappe disappear to the south beneath the shales and basalts of the Moma Nappe. The rocks at the contact are highly deformed and are divided into several blocks by two fault systems. The older system trends NNW, parallel to the

Figure 3 Hydrogeological map of Moneasa spa. *1* Quaternary alluvial deposits; *2* Triassic limestones and dolomites; *3* Upper Triassic shales and marls; *4* Permian basalts; *5* boundary between rock and drift; *6* fault; *7* thrust front (*symbol* on hanging site); *8* course of perennial stream (*arrow* indicates direction of flow); *9* perennial resurgent cave; *10* spring with hypothermal water (10–20 °C); *11* spring with mesothermal water (21–36 °C); *12* well with hypothermal water; *13* well with mesothermal water; *14* cliff line; *15* adit



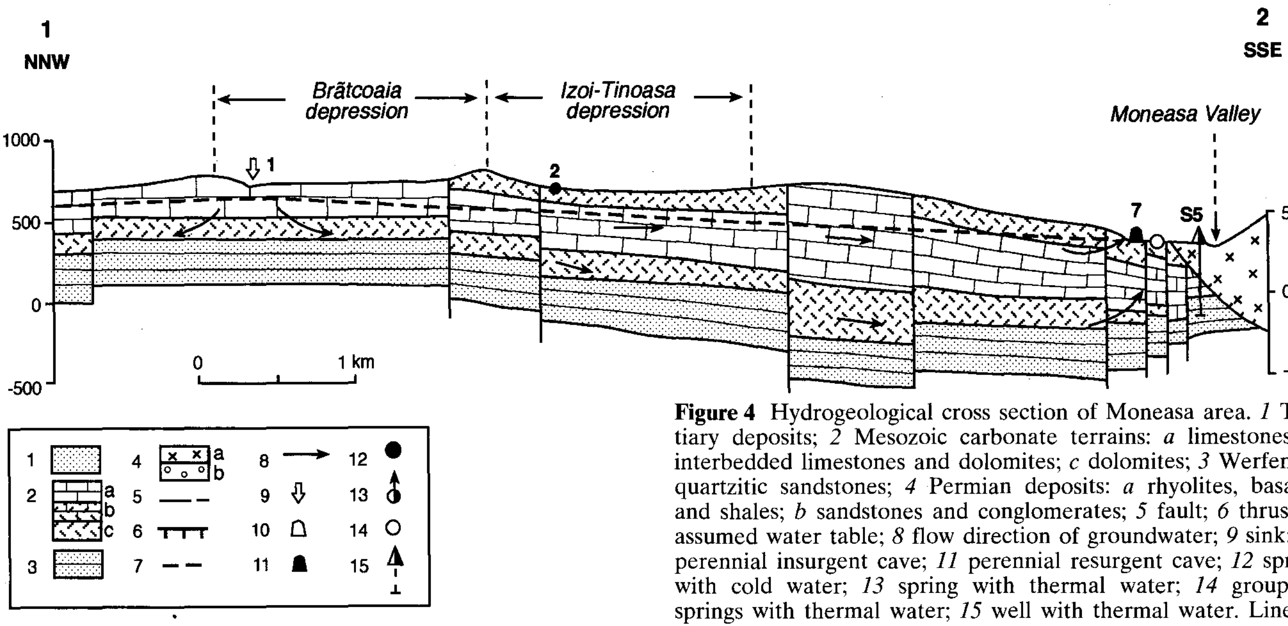


Figure 4 Hydrogeological cross section of Moneasa area. *1* Tertiary deposits; *2* Mesozoic carbonate terrains: *a* limestones; *b* interbedded limestones and dolomites; *c* dolomites; *3* Werfenian quartzitic sandstones; *4* Permian deposits: *a* rhyolites, basalts, and shales; *b* sandstones and conglomerates; *5* fault; *6* thrust; *7* assumed water table; *8* flow direction of groundwater; *9* sink; *10* perennial insurgent cave; *11* perennial resurgent cave; *12* spring with cold water; *13* spring with thermal water; *14* group of springs with thermal water; *15* well with thermal water. Line of section shown in *Figure 2*

strike of the rocks, and the newer one trends NE at right angles (*Figures 3* and *4*). Seismic and geoelectrical studies (Apostol et al. 1975), combined with data from groundwater boreholes, show that the thrust plane at the base of the Moma Nappe has a variable dip. The average dip is 55° toward the south, but close to the outcrop this increases to about 70°.

Hydrogeology

Most of the hydrogeological research that has been carried out in the Moneasa area is related to the exploitation of the thermal groundwaters. The first well was drilled during 1890–1895 to a depth of 316 m. The first measurements of the radioactivity of the thermal waters were made in 1927, but not until 1951 did the Institute of Balneology and Physiotherapy in Bucharest release the first complete chemical analysis of the groundwaters. Between 1970 and 1986, tracer experiments were carried out, firstly using tritium as a tracer and subsequently using rhodamine B, fluoresceine, iodine-131, and indium-EDTA (Gaspar and Oraseanu 1987; Oraseanu 1987). Between 1972 and 1987, additional wells were drilled to investigate the distribution of the thermal waters.

The tracer experiments demonstrated the presence of a major flow system originating from the depressions of Brătcoaia and Tinoasa/Izoi on the eastern slope of the Izoi summit (*Figure 2*). Iodine-131 and indium-EDTA tracers introduced into the Dosul Varului sinkhole situated in the northern part of the Brătcoaia depression (site 1 in *Figure 2*) show flow both northward to the Finis and Feredeu springs and southward to the Bear's Cave Spring and to the thermal springs and wells in the Moneasa River valley (Oraseanu 1987). Other tracer injections demonstrate flow from the Izoi depression to the Bear's Cave Spring and show that, during high recharge events, excess water that could not drain southward, because of the limited capacity of channels and fissures, drains eastward into the Meghes stream through outflow springs (sites 5 and 6 in *Figure 2*).

The Bear's Cave Spring was monitored during October 1975 to September 1976, when it had a mean discharge of 121.4 L/s and a minimum discharge of 32 L/s. The recession curve of the spring is characterised by three segments representing rapid flow through void spaces and major channels, slower flow through fissures and joints, and a baseflow component from the drainage of alluvium and debris within the voids.

The thermal waters at Moneasa, both natural spring discharges and those tapped by boreholes, are karst groundwaters that arise from the carbonate rocks of the Finis Nappe close to the contact with the Permian basalts of the Moma Nappe. The main natural sources are situated along the Baths Stream, downstream of the Bear's Spring. Locations are shown in *Figure 3*. The temperature of the water increases as the contact is approached, from 14.2 °C at spring (a) to 31.2 °C at spring (5). The increase in temperature with downstream distance from Bear's Cave is shown in *Figure 5a*.

The structure of the hydrothermal reservoir at depth was investigated by means of four boreholes drilled north and south of the thrust plane (S1, 2, 4, and 5 in *Figure 3*). Pumping tests were conducted in each of the boreholes, details of which are given in *Table 1*. Borehole S4 (*Figure 3*) was drilled very close to the contact and penetrated about 80 m of sediments of the Moma Nappe before encountering the thrust plane and entering limestones of the Finis Nappe. The results of the pumping tests in S4, shown in *Figure 6*,

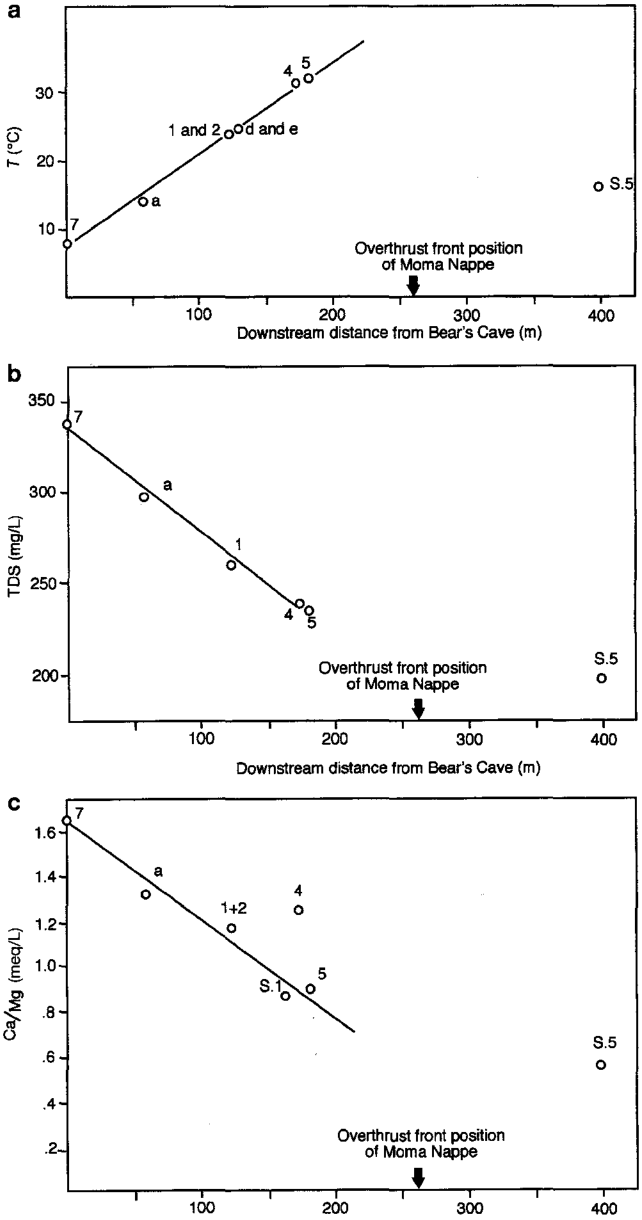


Figure 5 Relationship between distance from overthrust front of the Moma Nappe in the Baths stream and **a** temperature, **b** TDS, and **c** Ca/Mg

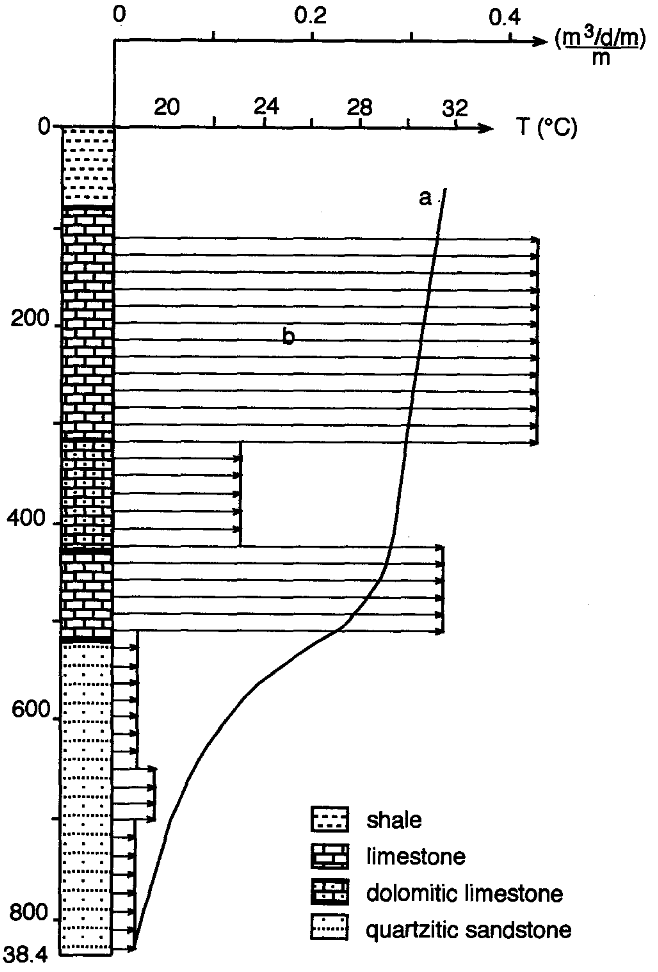


Figure 6 Relationship between depth and **a** temperature and **b** ratio between specific capacity and tested thickness interval in well S4

indicate that the temperature of the groundwater decreases with depth and that specific capacities (discharge in cubicmeters per day per meter of drawdown) as a ratio of the tested interval thickness (in meters) decreases with depth as a result of a reduction in fissure widths and the size of karst channels. Below 500 m, within quartzitic sandstone, both water temperatures and specific capacities decrease substantially (*Figure 6*).

A full-scale pumping test was performed in borehole S5. It was pumped at a constant discharge of 11.5 L/s for 120 h, with a final drawdown of 46.6 m. Fluctuations in the water levels were measured in wells S1, S2, and S4 during both drawdown and recovery. In addition, during the exploitation of well S1 for the baths of the spa complex, variations in water levels in well S4 were noted. The results show a distinct anisotropy; transmissivity (T) in a NNW direction, parallel to the strike of the rocks, is almost 600 m^2/d, and T values at right angles to this trend are about 200 m^2/d.

Groundwater Chemistry

Geochemically, the waters are divided into (1) those from the sinking streams, which are derived from the quartzitic sandstones and which have low total mineralisation; and (2) those from the carbonates. The chloride concentration is similar, about 7 mg/L in all the waters, and it is suggested that this concentration is derived from rainfall. Two main trends occur within the carbonate groundwaters. As the overthrust front of the Moma Nappe is approached and the temperature of the water increases, the concentration of total dissolved solids (TDS) declines. This trend is well shown along the course of the Baths Stream from the Bears Spring (7) to well 5 (*Figure 5b*). This general relationship is because the solubility of calcium carbonate decreases with increasing temperature, and, for example, calcite solubility decreases by about 20% when the water temperature rises from 10–25 °C.

The other trend in these groundwaters is an increase in the proportion of Mg as the overthrust front is approached. This trend is reflected in a decrease in the Ca/Mg ratio (*Figure 5c*). Because the solubility of dolomite decreases at a greater rate than that of calcite with increasing temperature, this is not a temperature effect. Rather, it reflects the greater contribution of groundwaters from deeper in the succession, where dolomites are the dominant lithology.

Vascau Plateau

Background

In the southern part of the Codru Moma Mountains, the carbonate deposits occur in the form of a discrete plateau, the Vascau Plateau, which covers an area of about 90 km^2 at a mean elevation of 600 m (*Figure 1*). More resistant non-calcareous rocks with greater relief

Table 1 Hydrogeological characteristics of wells in Moneasa spa. Elevations are in meters above mean sea level; piezometric and pumping levels are in meters above ground level

Well	Elevation (m)	Depth (m)	Piezometric level (m)	Discharge (L/s)	Pumping level (m)	Water temperature (°C)
S_1	292.59	316.0	+12.66	2.45	+0.14	24.0
S_2	302.59	604.0		0.40	+1.0	28.5
S_4	296.97	836.4	+8.45	3.0	+0.5	32.5
S_5	284.95	424.6	+24.62	7.0	+1.0	14.0

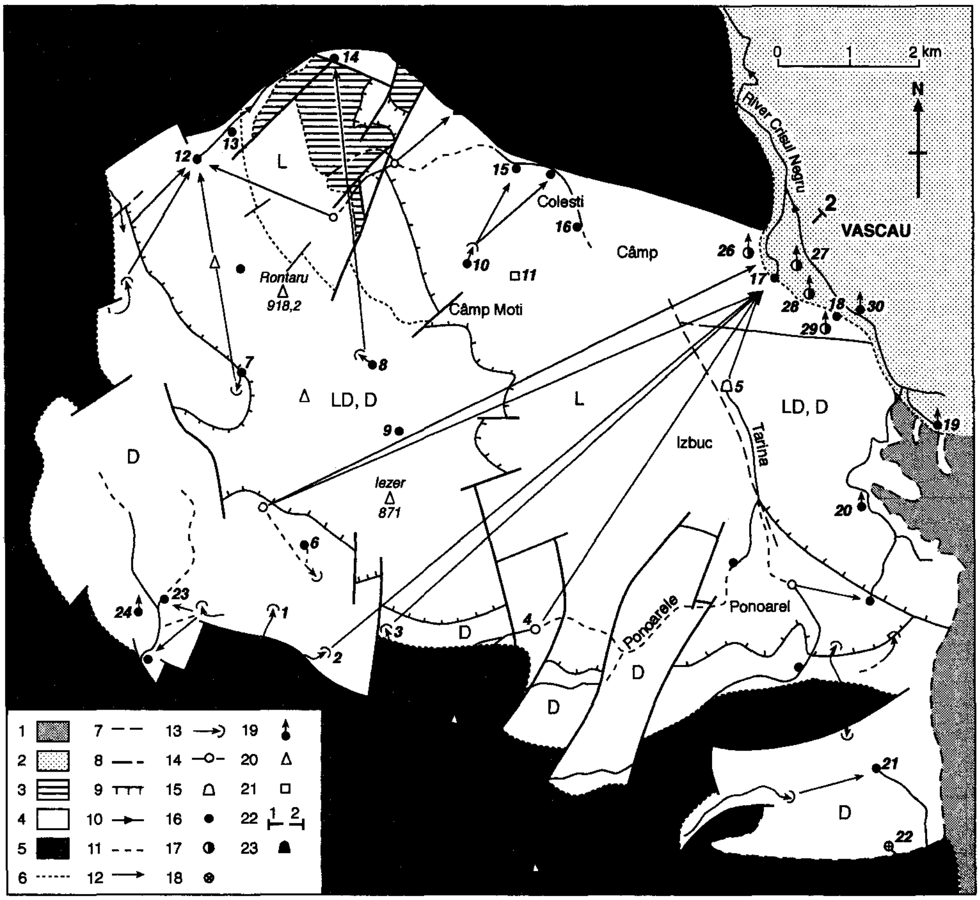


Figure 7 Hydrogeological map of Vascau Plateau (after Oraseanu 1985). *1* Recent and Quaternary deposits; *2* Tertiary deposits of Beius basin; *3* Lower Jurassic sandstones; *4* Triassic carbonate deposits; *L* limestones; *LD* dolomitic limestones; *D* dolomites; *5* Permian and Werfenian deposits; *6* boundary between rock formations; *7* boundary between rock and drift; *8* fault; *9* thrust front (*symbol* on hanging side); *10* course of perennial river or stream (*arrow* indicates direction of flow); *11* course of intermittent stream; *12* proven underground hydraulic connection between surface-water losses and resurgence; *13* sink; *14* losses in streambed; *15* perennial insurgence cave; *16* spring with cold water; *17* spring with thermal water; *18* flow-and-ebb spring; *19* gas outflow from spring; *20* summit (elevation above sea level in metres); *21* borehole; *22* position of hydrogeological cross section (see *Figure 8*); *23* perennial resurgence cave

border the northern, western, and southern margins of the plateau, thus defining a carbonate-floored amphitheatre facing the Beius depression to the east. The geology is shown in *Figure 7*. The topography of the plateau is dominated by high hills, extending from the northwest to the south-central area along the line of the Rontaru-Iezer summits (*Figure 7*). These hills define an uplifted area that slopes westward toward a series of large karstic depressions and slopes gently to the east as an extended flat area with sinkholes and dry valleys, crossed by the Tarina-Campeneasca karstic depression. At the eastern margin of the plateau, the elevation decreases abruptly along a series of NW-trending faults, until the carbonate rocks are buried beneath the Tertiary sediments of the Beius depression.

Frequent karstic-capture phenomena are responsible for diversion of the drainage system. Most of the surface waters on the slopes of the non-calcareous rocks bordering the plateau disappear into swallets that occur along the margin of the karst area. Thus, drainage entering the karst plateau from the south is lost through the West Ponoras (no. 1 in *Figure 7*), East Ponoras (no. 2), Recea (no. 3), and Ilii (no. 4) sinkholes. An exception is the Tarina stream, which collects waters from the southeastern part of the plateau and flows 5 km through a valley carved out of limestones down to the Campeneasca inflow cave (no. 5 in *Figure 7*).

On the basis of detailed geological mapping, the carbonate rocks of the Vascau Plateau are assigned to three separate tectonic units, known as the Moma, Vascau, and Colesti Nappes, and have a shallow dip to the east. The Moma Nappe is at the base and consists of igneous and sedimentary rocks of Permian and Werfenian age, overlain by a thicker sequence of black dolomites of Middle Triassic (Anisian) age. The upper part of the Moma Nappe and the overlying Vascau and Colesti Nappes consist of limestones and dolomites. The thickness of this carbonate succession increases toward the east, reaching a maximum of about 2500 m in the area of Vascau town (*Figure 7*). The whole sequence is compartmentalised by a series of subvertical faults, as shown by *Figure 7* and the section in *Figure 8*.

Solution of the limestones and dolomites has generated various karst forms. The orientation and density of sinkholes, dry and active valleys, and capture depressions are related to faults and thrust planes. The main orientation of landforms is N52°E, which corresponds to the principal stress axis in this part of the Codru Moma Mountains. The correlation coefficient between the two is 0.83, which demonstrates the strong tectonic control over the solution features.

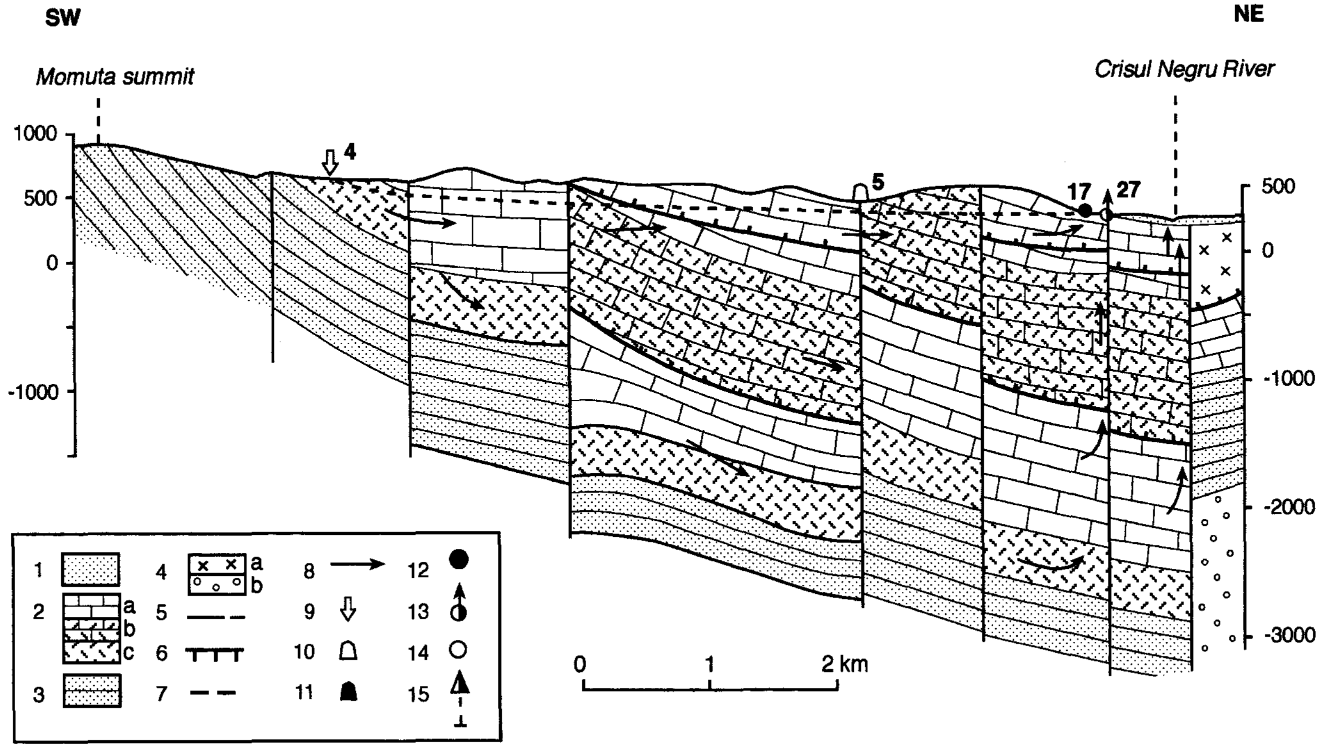


Figure 8 Hydrological cross section of Vascau Plateau. Legend as for *Figure 4*. Line of section shown in *Figure 7*

Hydrogeology

In general, the Permian and Werfenian deposits have low permeability, and groundwater circulation is confined to fractures and weathered zones. These deposits act as barriers to flow within the younger limestones and dolomites, where infiltration is rapid and groundwater circulation is active. Groundwater discharge from the karst area takes place via major springs around the perimeter of the plateau. During October 1986 to September 1987, mean discharges from these springs were as follows: Boiu (no. 17 in *Figure 7*) 588 L/s; Sopoteasa (14), 192 L/s; Tisa (12), 139 L/s; Crisciorel Fishery (20), 126 L/s; Valea Seaca (23), 77 L/s; Pepineaua (21), 67 L/s; and Raschirata (25), 43 L/s. Some springs also exist to the north, but these have smaller discharges (13, 15, and 16 in *Figure 7*). The karst groundwaters of the Plateau also recharge the Tertiary aquifers of the Beius Basin in the area of Vascau town and contribute about 100 L/s to the baseflow of the Crisul Negru River (*Figure 7*).

In addition to the major peripheral springs, other low-discharge springs occur on the plateau itself. These springs are related to crush zones associated with faults and thrust planes, which act as drainage systems for water in their immediate vicinity. Also, some are related to thin interbedded shales and to permeability differences amongst the carbonate rocks. These springs occur at the lowest intersection of the fault or impermeable bed and the topographic surface. After a short subaerial flow, they disappear into the stream bed or supply lakes where shales have enabled perched water bodies to form. These springs are epikarstic springs; examples are Banisoara (no. 6 in *Figure 7*), Fantana din Drum (7), Ponar Lake Spring (8), Valau Lake Spring (9), and Bobos (10).

The Vascau Plateau is probably the first place in Romania where water tracing was carried out. In 1904, the geologist S. Mihutia added powdered coal to the water of the Tarina stream and demonstrated a connection between the Campeneasca Cave (no. 5 in *Figure 7*) and the Boiu spring (no. 17). The tracer took 3–4 h to travel a distance of just over 1 km. Between 1978 and 1994, 15 tracer-injection tests were performed in order to establish groundwater flow directions. Rhodamine-B, fluorescein, optical brightener (stalex), iodine-131, and indium-EDTA tracers have all been used. The interconnections demonstrated are shown in *Figure 7* and many of the flowpaths are many kilometres in length. As can be seen from *Figure 7*, the Boiu spring is the main discharge point for the plateau.

On the western side of Vascau town (*Figure 7*), four thermal springs, associated with the outflow of gas, discharge from the karstic limestones of the Colesti Nappe, the alluvial deposits of the Crisul Negru River, and the stream leading from the Boiu spring (no. 17 in *Figure 7*). In addition to these thermal springs (numbered 26, 27, 28, and 29 in *Figure 7*), gas is observed discharging from four cold-water springs (numbered 30, 19, 20, and 24 in *Figure 7*). The temperature of the thermal springs ranges from

14.5–17.2 °C, and the cumulative mean discharge is 15 L/s.

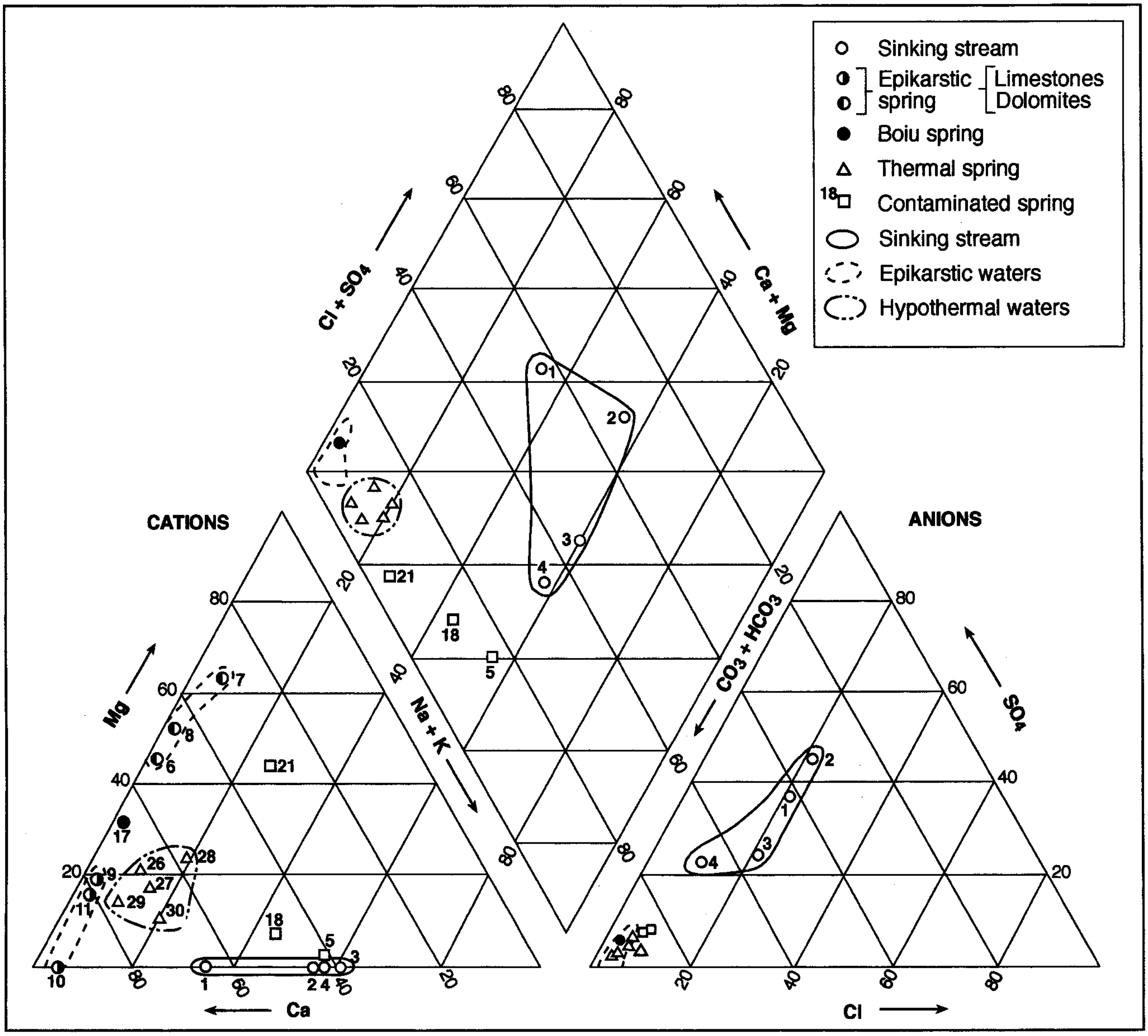
Near the southeastern boundary of the Vascau Plateau is the intermittent spring of the Calugari Monastery (no. 22 in *Figure 7*). The spring does not flow during dry periods, and the local karst network discharges through a perennial spring downstream. After rainfall, water backs up within the karst channels and the spring begins to flow between 1 and 30 min later. This ebb and flow spring is one of the scientific and touristic curiosities of the area.

Groundwater Chemistry

The thermal waters of the Vascau Plateau are similar in chemical composition to the cold karst groundwaters, and the gas differs only slightly from the atmosphere. A slight increase in the percentage of nitrogen occurs, probably as a result of the consumption of some oxygen by oxidation reactions. The chemical compositions of the main groundwater types are plotted on a Piper diagram in *Figure 9*. The waters from the sinking streams in the southwestern part of the plateau are distinctive; these waters, derived from the quartzitic sandstones, have a mean TDS of only 135 mg/L, a low pH of 5.3, and no Mg. The epikarstic springs are typical karst groundwaters, with a mean TDS of 421 mg/L. The main variation is in the Ca/Mg ratio, which is controlled by whether the springs arise from limestones or dolomites. A borehole at Oache (11) yields water of a composition that is similar to the epikarstic springs.

The discharge springs on the margin of the plateau plot in the same field as the epikarstic springs and

Figure 9 Piper diagram showing composition of waters from Vascau Plateau



only the major Boiu spring (17) is shown in *Figure 8*. Mean TDS is 435 mg/L. The thermal waters plot in a separate field and are intermediate in composition between the karstic waters and the sinking streams derived from the quartzites. However, the TDS (502 mg/L) of the thermal waters is higher than either of these waters. Three of the groundwaters are polluted. The water of the Tarina stream before it enters the Campeneasca Cave (5) and the Pepineaua Spring (21) have elevated concentrations of Na and K, probably as a result of domestic sewage pollution from the villages of Izbuc and Ponoarele, and the spring at Tucresti (18) is also polluted by a small stream.

Origin of the Thermal Waters

In both the Moneasa and Vascau Plateau areas, the thermal waters are associated with structural features close to major discharge points from the karst systems. At Moneasa, the thermal waters are immediately to the south of the Bear's Cave Spring, which tracer experiments show drains much of the area to the north (*Figure 2*); and on the Vascau Plateau, they are close to the Boiu spring, which drains over half of the plateau area (*Figure 7*).

At Moneasa, the limestones and dolomites are distinctly anisotropic. Transmissivity is about three times greater in a north/south direction, parallel to the strike, than in a perpendicular direction. Flow from the north is intercepted at the Bear's Cave Spring, close to the flow barrier provided by the low-permeability volcanics and sediments of the overthrust Moma Nappe. The thermal water is probably not related to the thrust plane itself, because borehole S5, which penetrates 275 m of Moma Nappe sediments, contains cooler water; the temperature is 17 °C, compared to the 32.5 °C of the hottest of the springs to the north. *Figure 6* also suggests that the thermal water arises from the carbonate rocks, because groundwater temperatures decline markedly in the quartzitic sandstones below 500 m. Rather, the thermal discharges are associated with the series of faults and fractures that were generated in the underlying Finis Nappe carbonate rocks by the overthrusting Moma Nappe. These faults and fractures allow deeply circulating thermal waters to move to the surface and blend with the cooler waters that recharge via the Brătcoaia and Tinoasa-Izoi depressions. The increased Mg concentrations in the thermal waters are derived from the deeper carbonates, which are dominantly dolomites (*Figure 4*).

Vascau town, on the eastern side of the Vascau Plateau, is close to the faults that divide the Codru Moma Mountain Block from the Beius Basin. These faults form a barrier to groundwater flow from the west, and most of the near-surface flow is intercepted by the Boiu spring. Deeper flow moves up the faults to mix with the colder water to form the thermal springs. Compositionally, the thermal waters are between the karst groundwaters and the sinking streams that are derived from runoff from the Permian quartzitic sandstones (*Figure 9*). Thus, the thermal component of the waters is probably at least partly derived from the Permian and Werferian deposits at depths of 1000 m or more beneath the surface.

In both areas, the thermal component of the springs is derived by deep circulation of mainly karstic groundwater in an area of relatively high heat flow. Both areas lie close to the Pannonian Basin (*Figure 1*), where heat flows of more than 95 mW/m^2 are recorded. The thermal water is brought to the surface by hydraulic barriers that intercept flow and allow water to move up faults and fractures and mix with cooler groundwater in the upper karstic units. This mixing accounts for the variations in temperatures among individual springs.

Conclusions

Both the Moneasa area and the Vascau Plateau contain major flow systems whose discharge is concentrated at one particular spring. At Moneasa, the flow direction is from the north to the south, parallel to the strike of the rocks. On the Vascau Plateau, the flow direction is from the southwest toward the northeast and is related to the principal stress axis in this part of the Codru Moma Mountains. The major spring discharges originate where the flow is intercepted by a hydraulic barrier. At Moneasa, this barrier is the overthrust plane of the Moma Nappe, and at Vascau town the barrier is the step-like system of faults that separate the Codru Moma Mountains from the Beius Basin.

At both locations, the hydraulic barriers also intercept flow at deeper levels. At Moneasa, thermal groundwater rises along faults and fractures associated with the thrust front; and at Vascau town, water rises along the faults marginal to the Beius Basin. Mixing of these waters with colder near-surface karst groundwaters in different proportions accounts for the differences in temperature among individual springs. The geochemistry suggests that the thermal component of the Moneasa groundwaters is derived from dolomites and that at least a proportion of the Vascau thermal waters originates from the deeply buried Permian sandstones.

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