International Association of Hydrogeologists

Jean-Jacques Risler
Ian Simmers
(editors)

Hydrogeothermics

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G. Castany, E. Groba, E. Romijn

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FOREWORD

The idea of publishing a monograph entitled "*Hydrogeothermics*" was launched by me when I was appointed Chairman of the IAH Commission on Mineral and Thermal Waters (at the CMTW meeting, Appingedam, Holland, 1986). The Commission members who approved the preliminary proposal for the project felt that there was a need for concise and up to date information on the hydrogeology, resources and use of thermal waters, if possible from every country where they occur. Such data are often scattered in inaccessible papers and unpublished reports, or at best in monographs concerned with only a limited group of countries (e.g. the European Community). Taking into account the growing interest in geothermal energy and its utilization, readily available information is of particular importance.

After comprehensive discussions which took place both during the Commission meetings (Bad Driburg, West Germany, 1987; Ladek Zdroj, Poland, 1988; Clermont-Ferrand, France, 1989) and in correspondence, the project started to make progress. The objective was the preparation of a concise monograph on the hydrogeology and use of thermal waters in various countries of Europe, as well as in the African and Asiatic countries of the Mediterranean region. This territorial coverage was determined mainly by the Commission members who declared their willingness to contribute chapters concerning their respective countries. It was considered that at a later stage the monograph could be extended to cover other regions.

The aims to be fulfilled by the monograph have been defined as follows:

- to compile updated information from all countries of the region (as specified above);
- to provide comparative data on methods of assessing geothermal resources as applied in various countries, as well as on legal, economic, environmental and technical problems related to the use of geothermal resources in these countries;
- to stimulate hydrogeothermal research in countries (especially the developing countries) in which, so far, it has not attracted adequate attention.

A scheme for the contents of each 'country' chapter was proposed. In particular, each chapter should include the following sections:

1. A general section providing basic data about the country, its geological setting, an outline of the history of hydrogeothermal research and development, legal aspects of geothermal exploration and exploitation, the methodology of hydrogeothermal resources assessment as applied in the country concerned, and its total energy balance.

2. A detailed section including the description of major hydrogeothermal systems and data on thermal water wells (or groups of wells), together with information on the present use of thermal water and the prospects for its further development.

3. A list of references including pertinent publications and, if appropriate, unpublished reports. Papers published after 1975 were initially to be presented in the form of an annotated bibliography, but this has proved to be impossible because of space limitations.

The above scheme was not intended to limit any initiative in presenting the hydrogeothermal problems of a country. It should be considered only as a guide to help to unify the form of the various chapters. Since in its first stage the monograph was supposed to comprise up to 35 'country' chapters, it was suggested that each chapter be limited to 20 pages. I undertook to coordinate the project.

In November 1989 the first six chapters, dealing with Czechoslovakia, Egypt, Hungary, Israel, Poland and the European part of the USSR were ready. They were sent to the IAH Secretary General Dr A.C. Skinner with the request to consider them for publication in the series "*International Contributions to Hydrogeology*" (published by Heise, Hannover) as the first volume of the monograph.

In the time that has elapsed between the submission of the texts by the authors and the publication of this volume many changes have occurred. The title of the chapter concerning the Soviet Union became out of date. There was also considerable development in research and the exploitation of hydrogeothermal resources in some of the countries concerned. Last of all, I have been appointed Polish ambassador to Israel, which has considerably limited my capacity to coordinate the project. Eventually, during the CMTW meeting in 1991 (in Jerusalem, Israel) Dr J.J. Risler was requested and agreed to take over these duties. I can only express my gratitude for the excellent though unrewarding job he has been doing.

The results of the Commission's efforts differ considerably from what was intended in the first, enthusiastic phase of the project. Nevertheless, I sincerely hope that in accordance with our original intention further volumes of the monograph will appear in due course. The second volume is intended to include chapters on Bulgaria, Germany, France, Iceland, The Netherlands and Switzerland. Chapters on Algeria, Austria, Belgium, Finland and Portugal are planned for the third volume.

May I take this opportunity to thank all the Commission members who supported the project and contributed to it, as well as those who are still preparing their contributions. Better late than never ....

Prof. Dr Jan Dowgiallo
(Chairman, IAH Commission on Mineral and Thermal Waters)

Tel Aviv, 1 July, 1992

ACKNOWLEDGEMENTS

The publication of IAH volume 15 ("*Hydrogeothermics*") has been a team endeavour; we acknowledge (*inter alia*) the support of IAH Council for initiating preparation of the camera-ready text.

Our special thanks go to Dr R.A. Downing, who evaluated the different chapters and undertook the task of editing and correcting the original manuscripts.

Jean-Jacques Risler
Ian Simmers
(Editors)

THE HYDROGEOTHERMAL POTENTIAL OF POLAND

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INTRODUCTION

General information

Poland covers an area of 312,683 km^2 with a total population of about 38 million. The mean annual temperatures range between 5,0 and 8,8°C depending on the region. Minimum and maximum temperatures are from −36,9 to −21,8 °C and from 31,8 to 38,2°C, respectively.

Geological setting (Figure 1)

The southernmost part of Poland belongs to the Carpathian foredeep and to the Carpathians. South of the Outer (flysch) Carpathians there are structures belonging to the Inner Carpathians (Pieniny Klippen Belt, Tatra Mountains) separated by the Podhale flysch basin.

The Hercynian structures of the Sudetes Mountains and of the Upper Silesian basin appear in the southwestern part of the country. The crystalline formations of the Sudetes are particularly favourable for the deep circulation of groundwater and for its geothermal heating.

The substratum of Central and North Poland (the Polish Lowland) may be divided into the northeastern part belonging to the east-European Precambrian platform and the northwestern part consolidated during Caledonian and Hercynian tectonic movements (Paleozoic platform). The border between these two main tectonic units is called the Tornquist-Teisseyre line, being a complex system of faults and flexures running from the Przemyśl area in the southeast, through the area of Lublin and Warsaw to Koszalin in the northwest.

Both platforms are covered with Permian and Mesozoic sediments forming secondary tectonic units elongated in the SE-NW direction. The main anticlinal structure is the Holy Cross Mountains - Kujawy - Pomorze anticlinorium. To the NE of it there is the so-called border synclinorium superposed over the Teisseyre-Tornquist line and divided into the Lublin, Warsaw and Pomorze parts. To the west is the Szczecin - Łodż - Miechów synclinorium. Its southwestern border is formed by the fore-Sudetic monocline, where Triassic sediments appear beneath the Cainozoic cover.

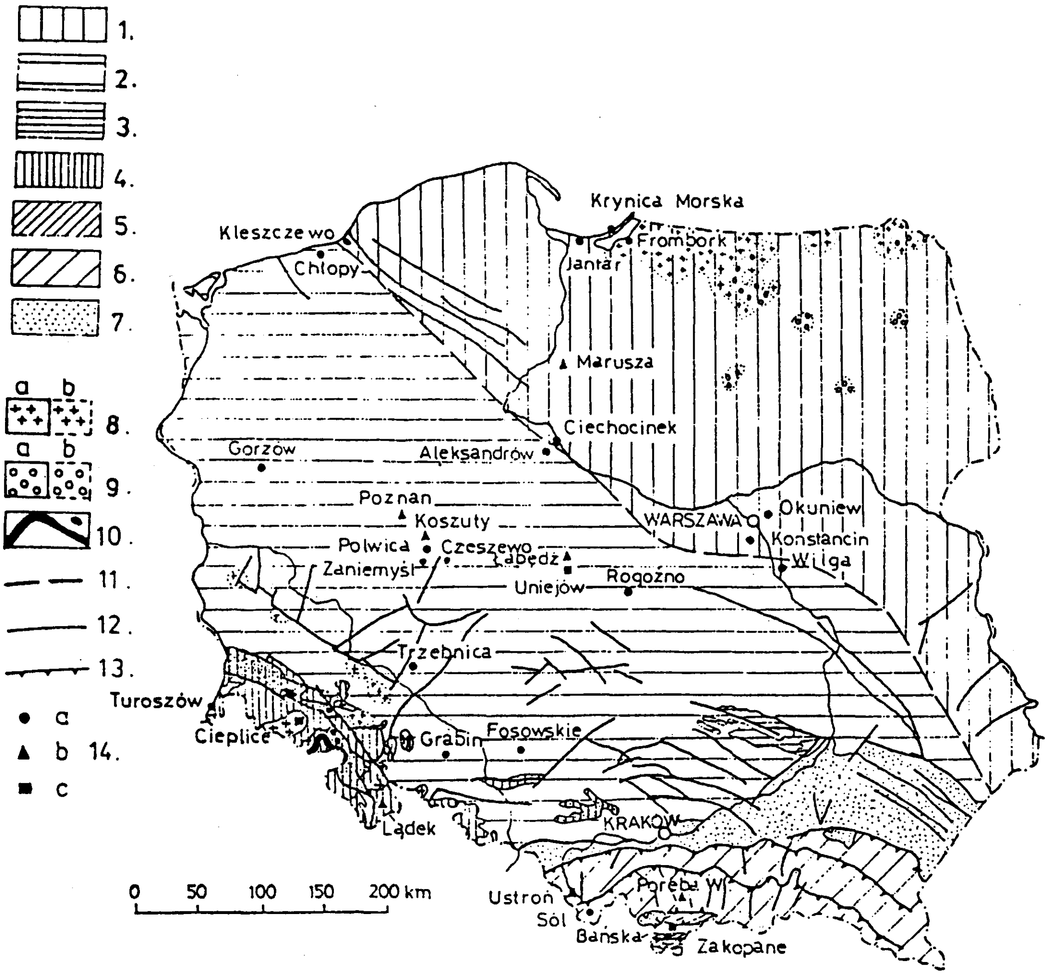

Figure 1: Present availability of thermal waters which could be used, against the background of the geology of Poland.

Legend: **1** - Pre-Cambrian platform; **2** - Paleozoic platform; **3** - Caledonids; **4** - Variscids; **5** - Pieniny Klippen Belt, high Tatric and sub-Tatric nappes; **6** - Flysch Carpathians; **7** - Orogenic intermontane basins and foredeeps; **8** - Granitoids, (a) on the surface, (b) under the rock mantle; **9** - Basic intrusions, (a) on the surface, (b) under the rock mantle; **10** - Volcanics; **11** - Teisseyre-Tornquist line; **12** - Faults; **13** - Overthrusts; **14** - Maximum water temperature at the outflow in °C, (a) 20-40, (b) 40-60, (c) >60.

Paleozoic and Mesozoic deposits are much thinner and less complete over the east-European platform than over the Paleozoic one, where they reach several thousands of metres. Rock salt of the Upper Permian (Zechstein) formations forms halokinetic structures often piercing through younger sediments. The only Caledonian structures appearing at the surface are the Holy Cross Mountains.

Legal aspects of geothermal resource exploration and exploitation

According to the definition used in Poland, thermal water is groundwater with a temperature of 20°C or more (Standard BN-74/9560-05, binding since 1.10.1974). The temperature should be measured at the outflow from a spring or at the mouth of a bore hole (President of the Central Geological Board, decree dated 5.5.1969). This definition concerns waters which may be used for medical purposes (therapeutic bathing and other kinds of treatment). This kind of direct use of geothermal energy is so far the only application of thermal waters in Poland.

A thermal water which has undergone clinical investigations may be declared a medicinal water by the Minister of Health and Social Welfare as stipulated by the decree of the Council of Ministers dated 16.3.1962 concerning the definition of mining resources, the extraction of which is amenable to the Mining Law. This means that it becomes a useful resource which belongs entirely to the State and must not be extracted without permission of a pertinent Mining Board. This permission, in turn, cannot be issued before the water resources are evaluated and approved by the Commission for Hydrogeological Documents of the Ministry of Environmental Protection and Natural Resources. Measures for the qualitative and quantitative protection of the water under consideration must also be established before the exploitation permit is given.

Qualitative protection aims at avoiding changes in water quality as a result of contamination, dilution or temperature drop. Quantitative protection is undertaken against water mining; i.e., its extraction in quantities exceeding the evaluated, exploitable resources. Until now thermal waters in five localities (Ciechocinek, Konstancin, Cieplice, Ladek and Zakopane) have been declared medicinal waters (Figure 1) and they are considered to be a useful resource, extracted under the rules of the Mining Law.

The evaluation of thermal water resources is based in Poland on the same principles as applied to water used for domestic, industrial and agricultural purposes as well as other types of medicinal waters. Besides natural (purely hydrogeological) criteria of resource evaluation, there are also technical, environmental and economic criteria which, in principle, limit the extraction allowed to the so-called exploitable resources.

Three types of groundwater resources are distinguished in practice: static, dynamic and exploitable resources. Static resources correspond to the quantity of water that can be removed from the aquifer as determined from the specific yield of a given aquifer volume. They are evaluated mainly for closed systems where groundwater is not renewable. Dynamic resources are the quantity of water flowing through a given aquifer section during a time unit. Dynamic resources are in principle renewable, while static resources may be renewable in some cases.

Exploitable resources correspond to the quantity of groundwater which may be extracted from an aquifer in a time unit provided that the exploitation: 1) does not exceed natural resources; 2) is not harmful to the environment and other users of groundwater and 3) does not negatively influence the quality of the water itself. Such resources may be evaluated for an aquifer, for a group of wells or for a single well. They are, in principle, renewable and, assuming certain simplifications, the hydrogeological studies required for the evaluation of static and dynamic resources are also the main basis for the evaluation of exploitable resources.

If exploitable resources are established for a single well or a group of wells, their evaluation is based on pumping tests or observations of the spontaneous outflow under steady flow conditions. If they are estimated for a whole aquifer or for part of an aquifer, they are usually expressed as yield in relation to a surface unit (e.g. $m^3/h/km^2$).

The categories or, more precisely, the levels of resource identification are "C", "B", and "A". The assessment of water resources in the "C" category is based mainly on a short pump test. In order to assess the resources of medicinal and thermal waters in the "B" category, water quality / quantity monitoring over one year is required. Resources in this category approved by the Commission for Hydrogeological Documents of the Ministry of Environmental Protection and Natural Resources, may be the basis for investment planning. Approval of resources in the "A" category (three years of quantity/quality monitoring) is indispensable before starting to implement an investment for the use of a thermal or medicinal water.

Total energy balance of Poland

The energy production is given in Table 1 as per the Statistical Yearbook 1987 (geothermal heat installed capacity was additionally evaluated).

Table 1: Energy production as per 1986.

Installed capacity	MW
Electric plants (total)	30921 (e)
Hydroelectric plants	2005 (e)
Heating plants (total)	23003.5 (t)
Geothermal heat	3.5 (t)

Poland's energy balance is tight and requires a considerable increase in production. Fossil fuels being the main energy source, are causing considerable air pollution and resulting in environmental damage. The development of geothermal energy for space heating is essential.

THE MAJOR HYDROGEOTHERMAL SYSTEMS

The Tatry - Podhale hydrogeothermal system

The system under consideration belongs to the Inner Carpathians and is situated between the Tatra Mountains in the south and the Pieniny Klippen Belt in the north. The Podhale basin is filled with Eocene nummulitic limestones and Eocene-Oligocene flysch. Both these series cover the sub-Tatric nappe structures consisting of Mesozoic sediments and extending up to the Pieniny Klippen Belt. Both the sub-Tatric nappes and the nummulitic limestones form a resourceful artesian basin. The heat flow in the region is estimated to be about 60 mW/m^2.

So far, thermal waters have been developed at Zakopane, where they are used in an open swimming pool, and at Bańska (Table 2). In the near future further drilling operations are planned in the Podhale region in order to provide thermal water for space heating and swimming pools.

Table 2: Thermal waters in the Tatry - Podhale region.

Locality		Zakopane	Bańska
Designation		Sub-Tatric nappe	Nummulitic limestone
Aquifer	Age	Triassic	Eocene
	Type	dolomite	limestone
Tapping depth (m)		1560	2600
Artesian yield (m^3/h)		50	60
Temperature (°C)		36	72
TDS (mg/l)		351	3700
Chemical type		HCO_3-SO_4-Ca-Mg+H_2S	HCO_3-SO_4-Cl-Na+B
Utilization	Present	swimming pools	--
	Future	--	space heating swimming pools

Thermal waters of the Outer (flysch) Carpathians

The distinction of individual hydrogeothermal systems in the Outer Carpathians (both within the flysch nappes and their bedrock) is hardly possible. The recharge areas for thermal waters are not known and, what is more important, their meteoric origin is doubtful. The waters under consideration are, as a rule, saline. Results from hydrochemical and isotopic investigations indicate they are most probably a mixture of marine relict waters with metamorphic waters originating from dehydration of clay minerals at considerable depths. The possible admixture of meteoric waters is probably ancient, and recent recharge plays a negligible role, if any.

The heat flow measurements performed by Plewa (1976) show that in the Outer Carpathians they vary from 42 to 67 mW/m^2. These values are lower than those observed in the Inner Carpathian region or in the former USSR and Czechoslovakia.

In the folded Carpathian region of the Ukraine, the heat flow ranges between 67 and 92 mW/m^2, while in the folded Carpathian region of Slovakia it is between 71 and 75 mW/m^2, reaching 113 mW/m^2 in the Neogene Basin. The values found in the Polish Carpathians are characteristic of the outer zone of the orogen. Still lower values were found in the Carpathian foredeep, where they range from 37.7 to 62.8 mW/m^2 in the Ukraine.

Thermal waters have been struck in many drill holes, mainly carried out for oil and gas. The water yield of the flysch deposits is, in principle, low and the high salinity of the thermal waters occurring in deep horizons hinders their use. The data for thermal wells that are in use or may be used in the future are presented in Table 3.

No synthetic evaluation of the geothermal resources in the Outer (flysch) Carpathians has been made so far. Jankowski *et al.* (1982) suggested, on the basis of geophysical investigations, the possible existence of considerable volumes of hot water beneath the Carpathian arc (probably below 8000 m). The presence of a metamorphic (dehydration) component in some Carpathian mineral springs, as shown by their oxygen and hydrogen isotopic composition (Dowgiałło & Leśniak, 1980) and the highly probable young or even recent metamorphism at these depths (Dowgiałło, 1980), seems to support this suggestion. In any case, the target depth of wells intended to tap waters hotter than 100°C would have to be at least 4000-5000 m.

Hydrogeothermal systems of the Sudetes

The Sudetic region, including both the Sudetes Mountains and the fore-Sudetic block, includes several hydrogeothermal systems. Two of them, namely the Cieplice and Ladek systems are fairly well known, while those of Turoszów and Grabin, where thermal waters had been found accidentally in one locality, require further detailed studies. Drilling operations have also to be carried out in order to verify the hypothesis about the existence of one or more hydrogeothermal systems in the Duszniki-Kudowa area (Dowgiałło, 1987).

The Karkonosze-Cieplice geothermal system is entirely connected with the Karkonosze Carboniferous granitic massif. Meteoric water, recharged probably in the main range of the massif (at altitudes up to 1600 m.a.s.l.), flows to the north and appears in thermal springs at Cieplice in the Jelenia Góra morphological basin. The thermal water of the Cieplice hot springs has been used for therapeutic treatment from time immemorial. The spring water temperature amounts to 45°C. Chemical geothermometry of thermal water indicates that it could reach a temperature close to or even exceeding 100°C during its underground flow path. Recently two boreholes drilled at Cieplice to a depth of 660 m (C-1) and 750 m (C-2) have shown that the temperature, yield and head of water increases considerably with depth. This makes it possible

Table 3: Thermal waters in the Outer Carpathians.

		Poreba W.	Sól	Ustroń
Locality		Poreba W.	Sól	Ustroń
Designation		Krosno Beds	Czarnorzeckie beds	Flysch bedrock
Aquifer	Age	Oligocene	Palaeocene	Devonian
	Type	sandstone	sandstone	limestone
Tapping depth (m)		1600	1300	1240
Yield (m^3/h)	Artesian	12	--	--
	Pumped	--	--	10
Temperature (°C)		42	35	50
TDS (mg/l)		21800	42500	90000
Chemical type		Cl-HCO_3-Na	Cl-Na	Cl-Na
Utilization	Present	--	--	Balneological treatment
	Future	Balneological treatment	Balneological treatment	--

to count the Cieplice hydrogeothermal system among the most promising in Poland, taking into account the low mineralization of water from the C-2 borehole, its high yield (50 m^3/h) and the temperature of the spontaneous outflow amounting to 63°C (Table 4).

The Snieżnik - Ladek Zdrój hydrogeothermal system is developed within the metamorphic formations of the Snieżnik Mountain (1425 m.a.s.l.) massif. The recharge is probably in the upper parts of the Snieżnik massif and the thermal water appears in springs at Ladek in the Biała Ladecka River valley. Thermal waters here have a very old tradition for therapeutic application. The spring water temperature amounts to 28°C, and it contains Rn and H_2S + HS^-, while the TDS is extremely low (200 mg/l). A borehole drilled in 1974 to a depth of 700 m (Table 4) resulted in a spontaneous outflow of thermal water at a temperature of 45°C and a simultaneous decrease in yield of the natural springs. Chemical geothermometry indicates that the maximum temperature reached by the water within the system might be 60°C.

Hydrogeothermal systems of the Polish Lowland

Thermal waters occur in Mesozoic and Paleozoic formations of the Lowland except for those parts of the east European platform where the sedimentary cover is thin and the heat flow low. However, due to the increase of salinity with depth only aquifers in the Lower Cretaceous,

Table 4: Thermal waters of the Sudetic region.

Locality		Cieplice	Lądek	Grabin	Turoszów
Designation		Karkonosze granite	Śnieżnik metamorphic series	Crystalline basement of the fore-Sudetic block	Runburg granite
Aquifer	Age	Carboniferous	Precambrian	Precambrian	Lower Paleozoic
	Type	fissured granite	fissured gneiss	paragneiss	fissured granite covered with Miocene clays
Tapping depth (m)		0 - 750	0 - 700	500	15
Artesian yield (including springs) (m^3/h)		60	60	150	60
Temperature (°C)		21 - 63	20 - 45	31	26
TDS (mg/l)		600 - 800	200	9800	4000
Chemical type		SO_4-HCO_3-Na+F	HCO_3-Na+H_2S+HS +Rn	HCO_3-Na-Mg+CO_2	HCO_3-Na+F
Utilization	Present	Balneotherapeutics, bottling	Balneotherapeutics, swimming pool	--	--
	Future	ditto	ditto	not yet decided	--

Jurassic and part of the Triassic can be taken into consideration for the development of thermal water for balneotherapeutic, recreation or heating purposes.

The occurrence of thermal waters in Mesozoic formations is linked to the main synclinorial units, divided by the anticlinorium which, at least in part, acts as the recharge area. It seems, therefore, reasonable to divide the area into the northeastern and southwestern parts, which may be considered as two separate hydrogeothermal systems, the southern parts of which are covered by the marine Miocene of the Carpathian foredeep.

The northeastern system is recharged from the southwest where Jurassic and even Triassic formations outcrop beneath the Cainozoic, as well as from the northeast where sedimentary and crystalline formations of the east European platform come close to the surface. The southwestern system is recharged both from its northeastern side (the Holy Cross Mountains - Kujawy - Pomorze anticlinorium) and from the southwest where, within the fore-Sudetic monocline, Jurassic and Triassic formations appear beneath the Cainozoic.

The highest heat flow values so far measured in Poland (up to 90 mW/m^2) occur within the southwestern system (Figures 2-5) which, consequently, is more promising in respect of the possible use of thermal water than the northwestern system.

Hundreds of boreholes drilled in the Polish Lowland by various organizations have struck thermal water. However, only in a dozen or so would the use of this water be economic and technically feasible as a result of appropriate high temperature, low TDS and considerable spontaneous yield (Tables 5 and 6). Further investigations will be concentrated in the most promising areas, where thermal water is likely to contribute considerably to the energy balance.

PRESENT UTILIZATION OF GEOTHERMAL RESOURCES AND FUTURE PLANS

Present utilization

The direct use of geothermal energy in Poland is at present negligible compared with fossil fuels and hydroelectric energy. In some health resorts, thermal water is used in swimming pools and for therapeutic purposes without additional heating (Table 7).

Future plans

Plans for the development of geothermal energy mainly concern the Tatry-Podhale region, the Sudetes and the western part of the Polish Lowland. Most probably, the first town to be heated by means of geothermal heat will be Nowy Targ, north of Zakopane. Preparatory work is also going on in both the other regions.

The development of thermal water for space heating and other purposes as foreseen in the future will certainly require the formulation of a new methodology for assessment of the exploitable resources.

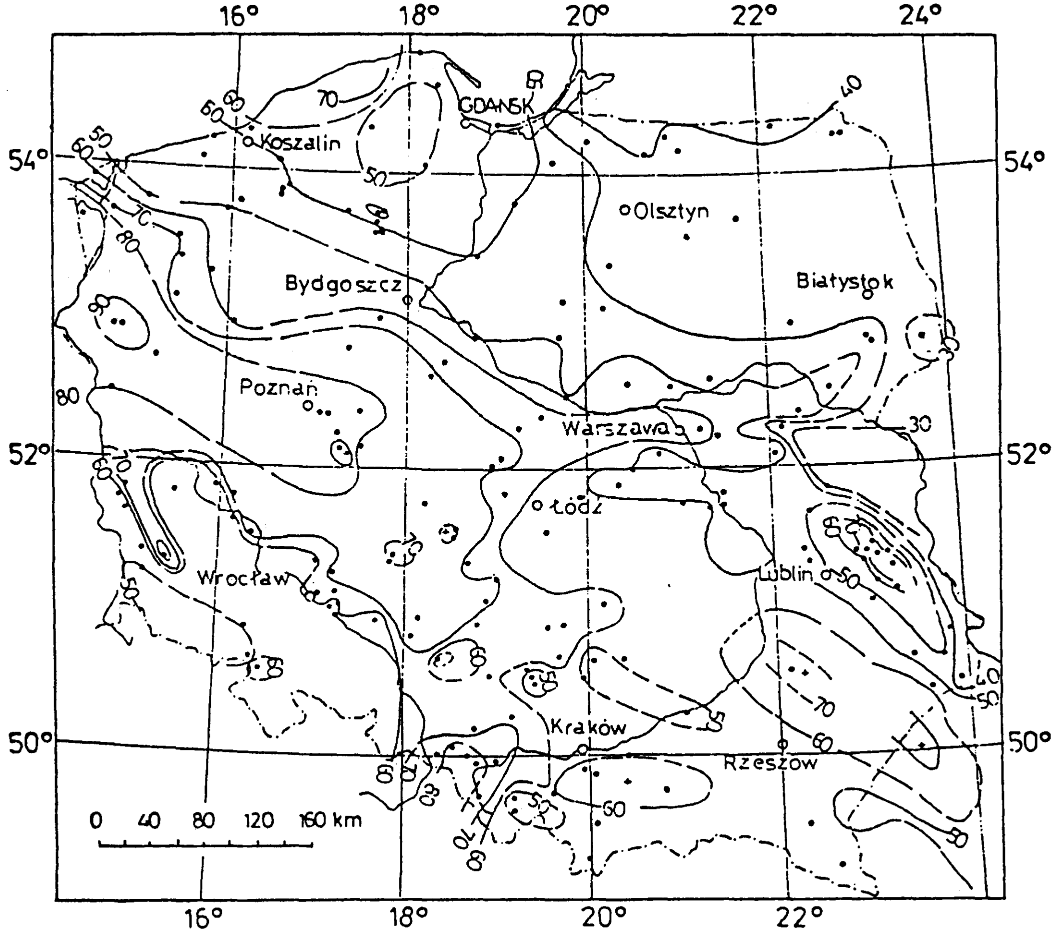

Figure 2: Surface heat flow distribution in Poland (mW/m²) (after Majorowicz & Plewa, 1979).

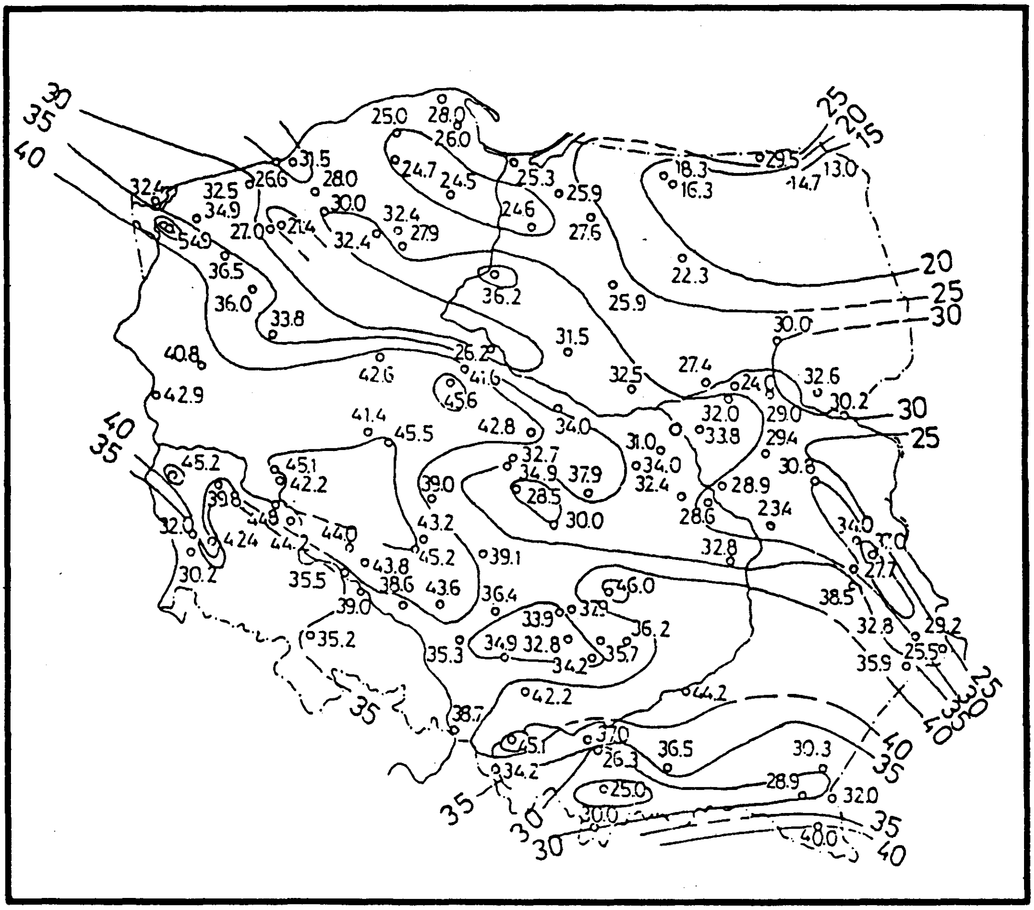

Figure 3: Map of geoisotherms in °C at a depth of 1 km (after Majorowicz & Plewa, 1979).

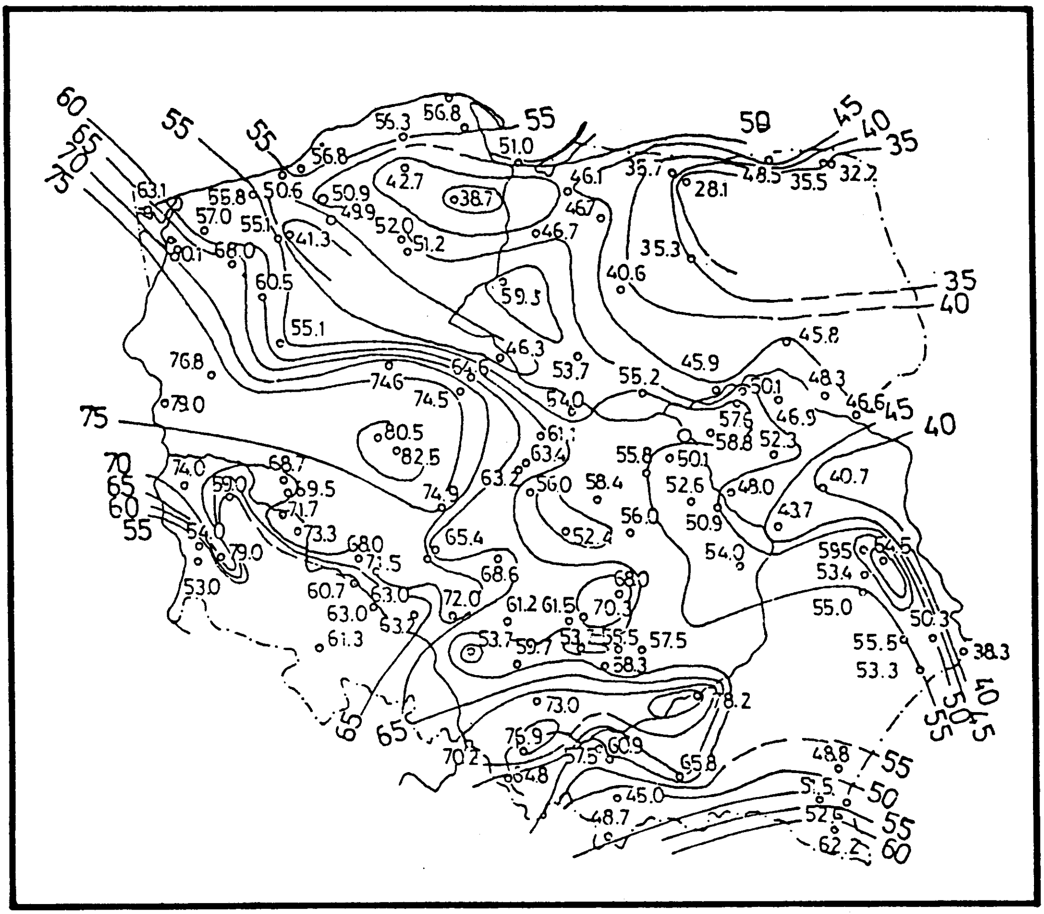

Figure 4: Map of geoisotherms in °C at a depth of 2 km (after Majorowicz & Plewa, 1979).

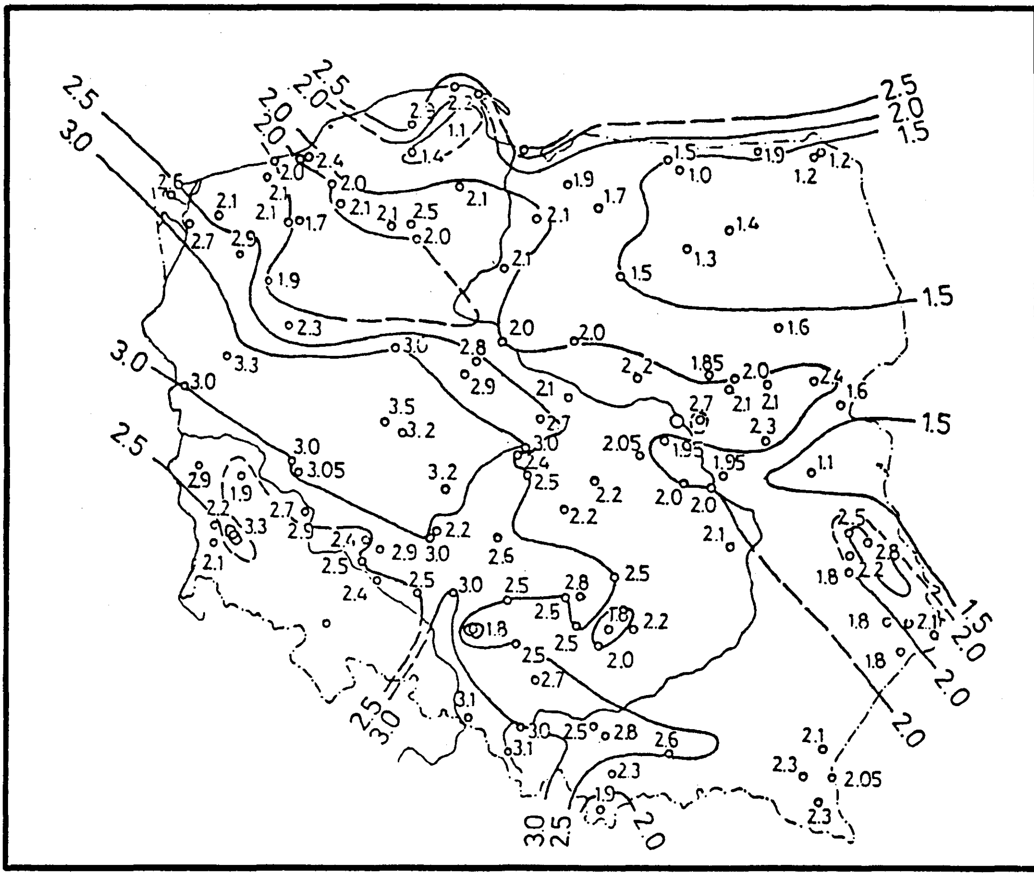

Figure 5: Map of isolines for weighted mean values of temperature gradient (in °C/100m) (Majorowicz & Plewa, 1979).

Table 5: Thermal waters in the Polish Lowland (southwestern hydrogeothermal system).

Locality	Aquifer		Tapping depth (m)	Yield (m^3/h)		Temp. (°C)	TDS (mg/l)	Chem. type	Utilization	
	Age	Type		Artesian	Pumped				Present	Future
Czeszewo	L. Jurassic	sandstone	960	15	--	35	4500	Cl-Na	--	not decided
Fosowskie	Triassic	sandstone	520	48	--	24	460	Cl-Na	--	not decided
Gorzów	L. Jurassic	sandstone	1020	18	--	37	64300	Cl-Na	--	not decided
Koszuty	L. Jurassic	sandstone	1020	40	--	40	8000	Cl-Na	--	not decided
Labędź	L. Cretaceous	sandstone	1800	80	--	60	6500	Cl-Na	--	not decided
Polwica	L. Jurassic	sandstone	1060	18	--	38	9000	Cl-Na	--	not decided
Poznań	L. Jurassic	sandstone	1150	76	--	42	21000	Cl-Na	--	not decided
Rogoźno	Jurassic	limestone	264	11	--	35	1500	Cl-Na	--	not decided
Przebnica	M. Triassic	limestone	860	--	9	32	3900	SO_4-Cl -Ca-Na	--	not decided
Uniejów	L. Cretaceous	sandstone	2080	65	--	67	8600	Cl-Na	--	not decided

Table 6: Thermal waters in the Polish Lowland (northeastern hydrogeothermal system).

Locality	Aquifer		Tapping depth (m)	Yield (m^3/h)		Temp. (°C)	TDS (mg/l)	Chem. type	Utilization	
	Age	Type		Artesian	Pumped				Present	Future
Aleksan-drów	L. Jurassic	sandstone	953	40	--	28	50000	Cl-Na	--	not decided
Chłopy	L. Jurassic	sandstone	900	8	--	23	70000	Cl-Na	--	not decided
Ciechoci-nek	L-M. Jurassic	sandstone	760-1360	500	--	27-37	43000-70000	Cl-Na	Balneo-logy	not decided
Frombork	L. Triassic	sandstone	1100	--	11	24	59000	Cl-Na	--	not decided
Jantar	L. Triassic	sandstone	960	44	--	22	50500	Cl-Na	--	not decided
Kleszczewo	L. Jurassic	sandstone	870	18	--	26	43000	Cl-Na	--	not decided
Konstancin	L. Jurassic	sandstone	--	--	8	30	70000	Cl-Na	Balneo-logy	not decided
Krynica M.	L. Triassic	sandstone	865	45	--	24	36700	Cl-Na	--	not decided
Marusza	L. Jurassic	sandstone	1630	50	--	42	78000	Cl-Na	--	not decided
Okuniew	L. Jurassic	sandstone	1150	--	10	24	53000	Cl-Na	--	not decided
Wilga	L. Jurassic	sandstone	1570	25	--	32	5000	Cl-Na	--	not decided

Table 7: Direct use of geothermal energy.

Locality	Average temp. of thermal water (°C) Inlet	Outlet	Average yearly yield (kg/s)	Utilized enthalpy (kJ/kg)	Average capacity (kW)
Ciechocinek	30	20	57	41	2337
Cieplice	40	20	2.7	83	224
Konstancin	30	20	0.1	41	4
Ladek	30	20	11	41	451
Zakopane	35	20	7	63	441
				Total :	3457

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HYDROGEOTHERMICS OF CZECHOSLOVAKIA

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INTRODUCTION

The former Slovak Socialist Republic (SSR; Slovakia) represents almost the only area where geothermal water (GTW) occurs in Czechoslovakia. For this reason legislation controlling the use of geothermal energy (GE) only applied in this part of Czechoslovakia. The exploration of GE resources commenced in Dionýz Štúr Institute of Geology, Bratislava, in 1971. By resolution 334/81 of the Slovak Government, the Slovak Ministry of Forest and Water Management was made responsible for the coordination of demands of individual divisions for GTW. Since 1981, all requirements concerning the drilling of geothermal wells in both the research and the consequent exploration-exploitation stages have been submitted to that Ministry. According to regulations issued by the Ministry in 1982, the tasks have been divided between the Ministry and the organs of State Administration.

District Committees control the GTW exploitation, and actual investigations are carried out by the Research Institute of Water Management, Bratislava. In accordance with resolution 45/1985 of the Slovak Government, the Slovak Geological Office carries out geological research and exploration of GTW; the Slovak Ministry of Agriculture and Food Industry is monitoring the effectiveness of GE utilization in agricultural plants (heating of glasshouses, plastic houses, etc); the Slovak Ministry of the Interior and District Committees cooperate closely in the complex utilization of GE, and the drilling of exploration-exploitation wells is only allowed in areas where investigations have been carried out; the Slovak Planning Commission controls the exploitation of GTW with respect to an energy programme. Since 1989 the Federal Ministry of Fuels and Energy, which has responsibility over National resources such as the Oil and Gas Industry, has also been concerned with the GE utilization. Geothermal research wells and/or research programmes for geothermal energy are paid from financial budgets for "science and technology"; the exploration-exploitation wells are financed from the "state budget" and from the "state fund for the water economy".

Economic cost efficiency of the programme for exploitation of GTW is evaluated according to the "criteria of average annual costs". This criterion is derived from the criterion of real costs in accordance with the regulations of the Federal Ministry of Technological Development Nr. 17/1981 concerning "evaluation of economic efficiency of fixed assets" and "methodological approaches" issued by the same Ministry for the purpose of the evaluation of fixed assets included in the "State programme of aims 02" of 1982.

From the point of view of hydrogeothermics the most suitable criteria are the economic size of the resource and/or the well yields (Table 1) in comparison with the efficiency of boiler plants for using natural gas and light heating oil. The controlling factors are an average geothermal gradient of 30 K/km, wells drilled to 2000, 3000 and 4000 m deep and exploitation by individual wells (without re-injection) and two wells (with re-injection). In 1985 the economic yield of wells without re-injection was 4-5 l/s and with re-injection about 22 l/s.

Table 1: Economic limits of energy efficiency and/or yields of geothermal wells (SINE, 1986).

Exploitation system	Well depth (m)	Limits of energy efficiency and yield of geothermal wells in comparison to boiler plants operating on natural gas and light heating oil	
		efficiency (MW_t)	yield (l/s)
Without re-injection	2000	(0,6)	(3,2)
	3000	1,2	4,0
	4000	2,5	6,0
With re-injection	2000	3,0	18,0
	3000	6,5	22,4
	4000	10,0	24,0

Exploited GTW are discharged after use into surface waters. In the sense of Resolution Nr. 30 of the Slovak Government on March 26, 1975, Table 2 defines the limits to avoid contamination of surface waters.

Laboratory studies have shown that it is possible to discharge thermal waters into the urban sewerage system (Pôbiš, 1982). An experimental purifying plant has been constructed for the purification of waste waters by activated sludge. The experiments have proved that the activated sludge raised from the city waste water can, by gradual processing, be adapted to the presence of a high content of geothermal waters during the purification of urban waste waters.

GTW are exploited by free outflow from individual wells. Exploitation by re-injection (using two wells) is ready for testing experimentally. Depending upon their properties the waters for heating are utilized directly, through heat exchangers, and with corrosion inhibitors through exchangers.

Table 2: Values defining limits of contamination.

T	Soluble O_2	Soluble matter	Cl^-	SO_4^{2-}	F^-	NO_3^-	Ca^{2+}	Mg^{2+}	NH_4^+	Fe^{2+}	Mn^{2+}	pH
°C	Saturation %						(mg/l)					--
max.	min.						max.					
26	50	1000	400	300	2,4	50	300	200	3,0	1,5	0,5	5,0-9,0

Exchangers and corrosion inhibitors are made in Czechoslovakia. In Czechoslovakia low-power (about 100 kW) heat pumps are used to extract heat from waste GTW with temperatures of about 20°C.

Heat energy potential (HEP) of GTW resources and reserves has been classified into three categories: prospective, prognostic and verified by wells.

Prospective HEP of GTW resources (exploitation by individual wells) is evaluated on the basis of the general knowledge of hydrogeothermal activity in the region. The activity is controlled by the presence of favourable aquifers, by the geothermal gradient, sub-surface temperatures and heat flow. The resources are evaluated by means of a geothermic balance expressing the energy equilibrium between the heat supplied by the heat flow, and the heat transported by water to the surface according to the relation (Franko, 1980):

$$V = q / [(T - t).c\rho] \qquad (1)$$

where V = specific yield ($m^3/s/m^2$)
q = heat flow density (W/m^2)
T = reservoir water temperature (°C)
t = temperature of neutral surface or average annual air temperature (°C)
c = specific heat of water (J/kg/K)
ρ = specific weight of water (kg/m^3)

Prospective HEP of GTW reserves (exploitation with re-injection) has been evaluated on the basis of general knowledge of the distribution of aquifers, geothermal activity and reliable data from non-geothermal wells. By analogy, the results from one region are applied in other prospective regions, bearing in mind the economic limits with respect to different geothermal gradients in different regions.

Prognostic HEP of GTW resources has been evaluated by hydraulic methods based on the results of individual geothermal wells drilled in one region. In the evaluation of the yield of the area the type of hydrogeologic structure is considered.

Prognostic HEP reserves of GTW are evaluated on the basis of at least one or possibly two geothermal wells in one area (see below - HEP reserves verified by well).

HEP of GTW resources verified by well has been evaluated separately for individual geothermal wells on the basis of the results of hydrodynamic tests. It is the verified HEP of a well that is recommended for exploitation.

HEP of GTW reserves verified by well has been evaluated for one pair of wells. Re-injection schemes are evaluated as for the cases of prospective and prognostic HEP of reserves.

CHARACTERISTICS OF MAJOR HYDROGEOTHERMAL SYSTEMS

Geology

The Czechoslovak territory consists of two structural units: the Bohemian Massif and the West Carpathians (Figure 1).

The Bohemian Massif is part of Meso-Europe and consists of the post-Variscan platform cover and of the Variscan consolidated basement. The consolidated basement is mostly composed of acid and mafic igneous rocks and metamorphic rocks. The platform cover is made up of pelite detrital Permian - Carboniferous formations and Neogene molasse sediments.

The West Carpathians consist of the Alpine folded mountain system, Tertiary basins and lowlands. The mountain range is divided into the Outer West Carpathians (Cretaceous and Paleogene flysch sediments) and the Inner West Carpathians. The so-called Klippen Belt (carbonate klippes enveloped by flysch sediments) lies between them. The Inner West Carpathians are characterized by abundant pre-Late Carboniferous crystalline schists, Variscan granitoids, Late Paleozoic sediments and volcanics, predominant Mesozoic carbonates, a pre-Senonian nappe structure, indications of Alpine metamorphism, the origin of granitoids, post-Cretaceous vertical movements during the formation of sedimentary basins, and by tectonic reworking into morphostructural elevations (mountain ranges) and depressions (basins and lowlands) with, very commonly, post-nappe, i.e. Paleogene and Neogene, sedimentary and volcanic formations.

Geothermal features of the system

The regional distribution of geothermal potential in Czechoslovakia is presented in the form of a map of geoisotherms at a depth of 1000 m below ground level (Figure 2). The map shows the striking difference in thermal activity between the Bohemian Massif and the West Carpathians (Král, *et al.*, 1988).

The Bohemian Massif is characterized by a weaker thermal activity than the West Carpathians. The most active areas are the northwestern part of the Bohemian Massif and the area of the

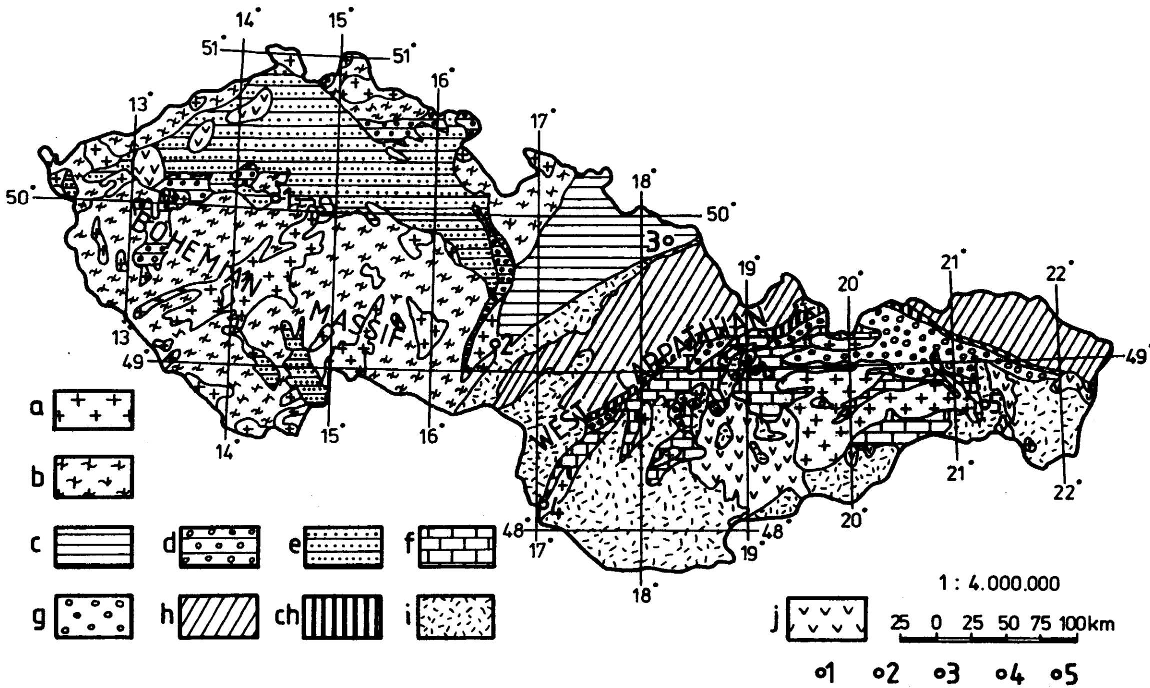

Figure 1: Schematic geological map of Czechoslovakia.

Legend: **(a)** - Crystalline complexes (acid and basic igneous rocks - Bohemian Massif; in the West Carpathians also metamorphites); **(b)** - Crystalline complexes (metamorphites - crystalline schists in the Bohemian Massif); **(c)** - Carboniferous (flysch facies); **(d)** - Permocarboniferous (shales, siltstones, sandstones, conglomerates); **(e)** - Cretaceous (claystones, marlstones, sandy marlstones, sandstones); **(f)** - Mesozoic (claystones, sandstones, limestones, dolomites, quartzites, organodetrital limestones, marly limestones); **(g)** - Inner Carpathian Paleogene (flysch facies); **(h)** - Cretaceous and Paleogene (outer flysch belt - flysch facies); **(ch)** - Klippen Belt (carbonate klippes enveloped in flysch sediments - Mesozoic and Paleogene); **(i)** - Neogene (conglomerates, clays, marls, sands); **(j)** - Neovolcanites.
Locations: **1** - Praha; **2** - Brno; **3** - Ostrava; **4** - Bratislava; **5** - Košice.

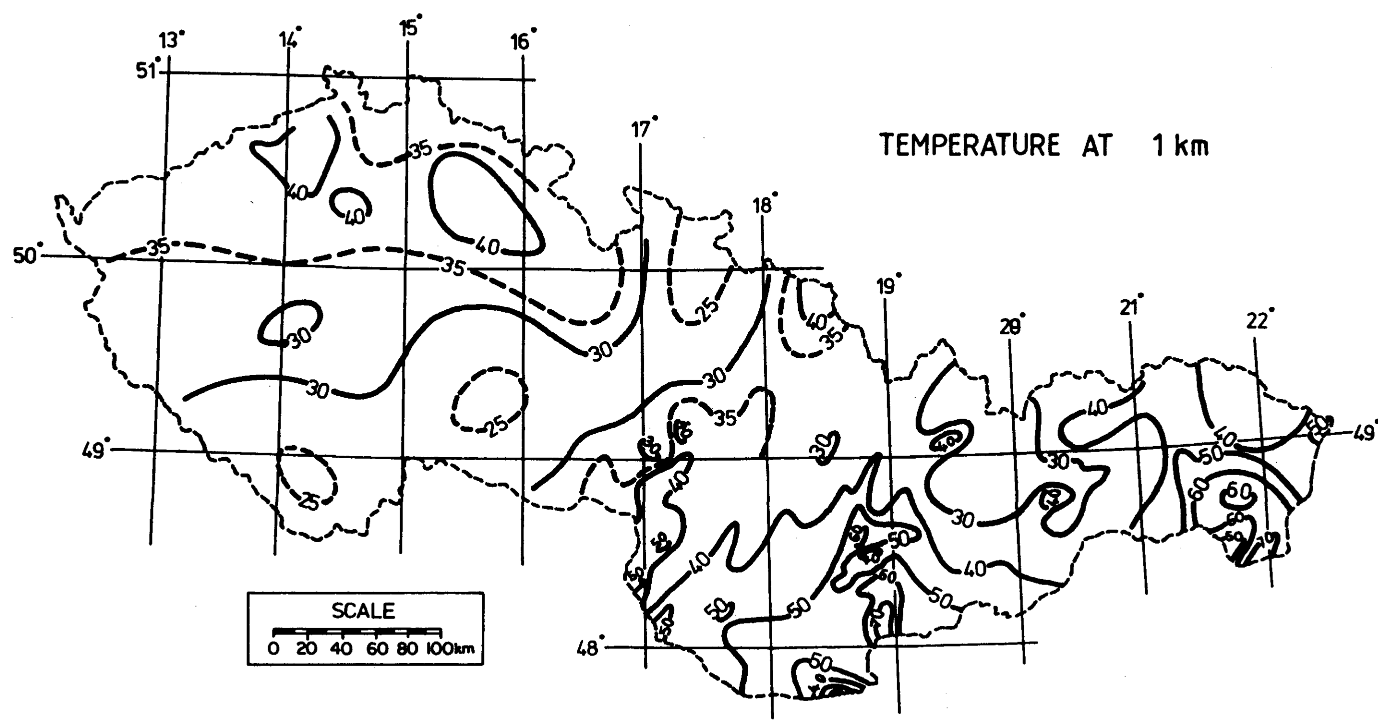

Figure 2: Map of geoisotherms (in °C) at a depth of 1 km below ground level.

Bohemian Cretaceous basin. The highest temperatures are associated with the thermal line of the central fault of the Ohře rift (temperatures about 45°C at a depth of 1000 m), and with the Teplice zone. Higher temperatures are found around the Labe tectonic-volcanic zone and in the area below the Krušné hory Mts. Temperatures lower than 30°C at a depth of 1000 m are characteristic of the southern and eastern parts of the Bohemian Massif (the area of Moldanubicum) and of the area of Jeseniky Mts. In the remaining parts of the Bohemian Massif the temperatures at a depth of 1000 m are about 30°C.

In the West Carpathians the temperatures are remarkably variable. Differences between individual geologic areas range from about 30°C at a depth of 500 m to 100°C at a depth of 4000 m. In almost the entire inner West Carpathians are the temperatures and geothermal gradient higher than to the north of the Klippen Belt. Extremely low temperatures have been found in the area of the Slovenské rudohorie Mts. In the regional context the geothermal activity of the West Carpathians decreases from the internal structures toward the external Carpathian arch.

The map of geoisotherms at a depth of 1000 m shows the division of the West Carpathians into two parts differing in thermal activity and spatial distribution of heat flow. One part comprises the Outer Carpathians, the northern and central parts of the Inner Carpathians; the other, thermally more active part, comprises a volcanic arch and adjacent intramontane basins, and the Neogene basins of the Inner Carpathians.

At the contact between the West Carpathians and the Bohemian Massif the average temperature is 35°C at a depth of 1000 m. Local anomalies above 40°C occur in the southern part of the Ždánický les and Chřiby Mts. An anomaly of more than 40°C, of a regional character and extending into Poland, is located in the area of the Ostrava-Karviná basin. Lower temperatures (below 30°C) have been found in the northern part of the Ždánický les Mts. In the remaining part of the territory the pattern of the thermal field is uniform, with temperatures about 35°C at a depth of 1000 m.

Thermal conditions were used for a study of dry rock heat. On the basis of maps of temperatures of 130° and 180°C the Czechoslovak territory has been divided into regions for the purpose of forecasting the amount of dry rock heat (SINE, 1986).

The areal distribution of the heat flow in Czechoslovakia (Čermák, 1979) is shown in Figure 3. The average heat flow in the *Bohemian Massif* is 60 mW/m^2. The maximum values (70-80 mW/m^2) have been found in the northwestern part of the massif (Krušné hory Mts., graben below the Krušné hory Mts.), on the intersection of the Ohře and Labe faults and in the Bohemian Cretaceous basin. The minimum values (30-40 mW/m^2) have been found on the northern periphery of Třebič pluton and in Jeseniky Mts. Heat flow values in the intermontane stable block are 50-60 mW/m^2.

Heat flow at *the contact between the Bohemian Massif and the West Carpathians* increases moderately from west to east. In the southern part of the Carpathian Foredeep it ranges from 42 to 72 mW/m^2; its average value is 54 mW/m^2. The increase from the southwest to the northwest along the Carpathian Foredeep is interesting. In the central part values range from 42 to 76 mW/m^2 and the average is 60 mW/m^2. Higher values with an average of 83 mW/m^2 are

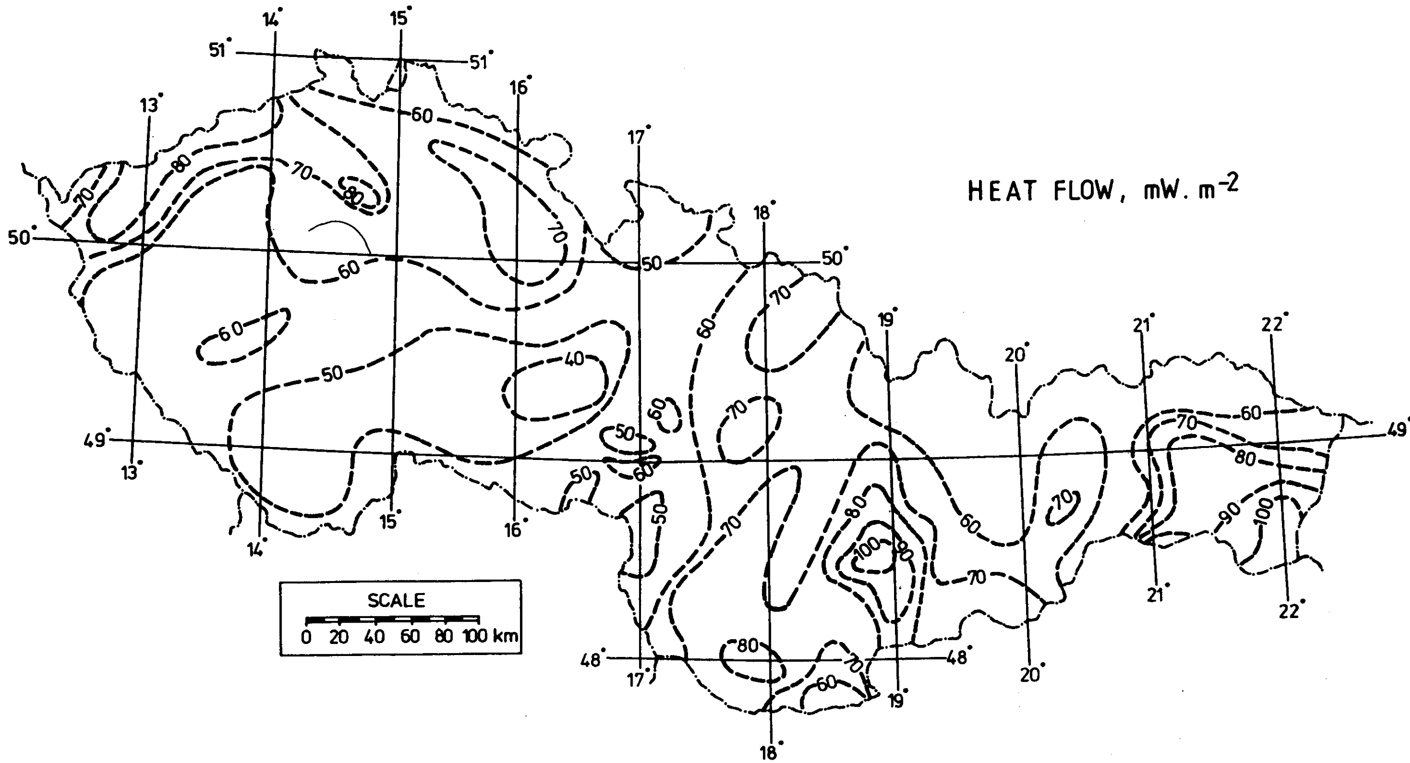

Figure 3: Map showing the areal distribution of heat flow (in mW/m^2) in Czechoslovakia.

characteristic of the Ostrava-Karviná coal district including the wider surrounding area.

In the *West Carpathians* the heat flow is variable. In regional terms it decreases from the Inner Carpathians towards the outer arch. The highest heat flow value has been found in the East Slovak basin (above 100 mW/m^2), which is part of the Pannonian basin. In the Central Slovakian neovolcanic region, high heat flows range from 74 to 109 mW/m^2. Higher values exceeding 80 mW/m^2 occur in the central part of the Danube basin. Heat flows of less than 60 mW/m^2 are to be expected in the northern part of the Inner West Carpathians and in the eastern part of the Outer Flysch. Low values, below 50 mW/m^2, occur in the Vienna basin. In the remaining part of the country values range from 65-70 mW/m^2 and no regionally interesting anomalies have been found.

Based upon a knowledge of the geological setting and the values of temperature and heat flow, and using Muffler's (1975) classification, we can classify the Bohemian Massif and the northern part of the West Carpathian among areas of normal heat flow (about 60 mW/m^2). The southern part of the West Carpathians and/or northern parts of the Pannonian basin can be classed with areas that are not associated with recent volcanism. Heat flow in these areas is higher than normal (for example in the Pannonian basin: 80-140 mW/m^2).

Hydrogeology and origin of thermal waters

Significant GTW resources in the *Bohemian Massif* are associated with fissure-vein systems in crystalline massifs (Karlovy Vary - 72°C, Jáchymov - 34°C, Velké Losiny - 36°C, Jánské Lázně - 28°C) and in quartz porphyries (Teplice v Čechách - 39°C). The spas Karlovy Vary and Teplice v Čechách are located in a graben below the Krušné hory Mts., which corresponds to a rift structure (Ohře rift). Jáchymov is in the Krušné hory Mts., Jánské Lázně in the Sudety Mts. and Velké Losiny in the Jeseniky Mts. Significant GTW resources are found in the Bohemian Cretaceous basin in the area of the České středohoři Mts. (Ústi n/Labem - 28,5°C, Děčin - 27°C). The waters are associated with Middle Turonian and Cenomanian permeable sandstones. Locally the waters are associated with Devonian limestones in Morava (Teplice n/Bečvou - 23°C). The waters are meteoric waters with a mineralization due to water-rock interaction. The chemistry of GTW in the graben below the Krušné hory Mts. (Karlovy Vary, Teplice v Čechách) indicates epigenetic evaporite mineralization that causes high Na^+, SO_4^{2-} and Cl^- contents.

Total discharge in natural discharge areas (springs, wells) is 280 l/s of water with a temperature range of 15-70°C. Over an area of 79 000 km^2 of the former Czech Socialist Republic the specific runoff is about $3{,}5 \times 10^{-3}$ l/s/km^2. This value is good evidence of the low geothermal activity of the Bohemian Massif. Wells drilled in discharge areas have tapped about 42 l/s of water with temperatures ranging from 15 to 40°C. A classification of thermal waters according to temperatures and lithological-stratigraphical range is presented in Table 3.

The West Carpathians are very rich in GTW. They are most common in the Inner West Carpathians and associated with the Middle and Late Triassic dolomites and limestones of nappes and envelope units. Aquifers have fissure and fissure-karst permeability. They are mostly in intramontane depressions, in the northern part of the Danube basin and in the Transdanubian Mid-mountains in the basement below Tertiary sediments. Waters discharge from these aquifers

Table 3: Thermal waters of the Bohemian Massif.

Discharge area	Temperature (°C) 15 - 20	20 - 30	30 - 40	40 - 70	70 - 100
	Yield (l/s)				
Crystalline rocks :					
natural	1,5	26,0	--	25,0	40,0
artificial	--	1,3	9,1	--	--
Devonian :					
natural	--	16,5	--	--	--
artificial	10,0	--	--	--	--
Cretaceous :					
natural	--	--	--	--	--
artificial	--	157,0	14,0	--	--
Tertiary :					
natural	--	--	--	--	--
artificial	--	21,5	--	--	--
Total :	11,5	222,3	23,1	25,0	40,0

in the Spas of Piešťany (70°C), Trenčianske Teplice (40°C), Rajecké Teplice (39°C), Turčianske Teplice (44°C), Lúčky (32°C), Liptovský Ján (28°C), Gánovce (25°C), Vyšné Ružbachy (22°C), Malé and Velké Bielice (39°C), Chalmová (39°C), Bojnice (48°C), Vyhne (36°C), Sklené Teplice (53°C), Sliač (33°C), Patince (27°C), Štúrovo (40°C), Kalinčiakovo (26°C), Malinovec (27°C), Dudince (28°C), Šafárikovo (18°C), Sobrance (30°C) and at many other localities with lower water temperatures. Significant resources are represented by GTW of Miocene-Pliocene sands and sandstones of the Danube- and the South Slovak basins. Less significant are GTW resources in basal Paleogene and Neogene clastics and crystalline complexes. These waters are not discharged from natural springs but from wells. On the surface the water temperature is 18-92°C. The total yield of natural discharge areas (springs, wells) is about 1030 l/s of waters with temperatures of 15-70°C. Over an area of about 49,000 km^2 of the former Slovak Socialist Republic the specific runoff is about 21 × 10^{-3} l/s/km^2. A comparison with the Bohemian Massif (3,5 × 10^{-3} l/s/km^2) indicates the very intensive geothermal activity of the West Carpathians.

Wells drilled in discharge areas yield about 700 l/s of GTW. Waters discharging naturally are of meteoric origin with a mineralization due to water-rock interaction. Waters from Triassic carbonates are carbonate and sulphate waters, but many of them are carbonate-sulphate or sulphate-carbonate waters. Some waters are of a mixed type due to carbonate-sulphate-chloride mineralization. Waters from Triassic carbonates, tapped by wells in the Vienna-, Danube- and East Slovak basins in the basement below the Neogene, are of the chloride type. Waters from one structure in the Vienna basin are meteoric but also have a mineralization of marine origin. Waters of the Pannonian basin in the Danube lowlands are meteoric to a depth of 1000-2500 m and have a composition related to hydrosilicate mineralization. At deeper levels they pass into chloride waters with a mineralization of marine origin. In the East Slovak basin chloride waters with a mineralization of marine origin are relatively common. A classification of thermal waters according to temperature and lithological-stratigraphical range is given in Table 4.

Table 4: Thermal waters of the West Carpathians.

Discharge area	Temperature (°C) 15 - 20	20 - 30	30 - 40	40 - 70	70 - 100
	Yield (l/s)				
Crystalline rocks :					
natural	--	--	--	--	--
artificial	5,1	--	--	--	--
Triassic :					
natural	414,0	292,0	182,0	139,0	--
artificial	32,0	16,0	185,0	53,0	--
Paleogene :					
natural	--	--	--	--	--
artificial	--	19,2	--	--	--
Neogene :					
natural	3,8	--	--	--	--
artificial	12,0	27,8	66,3	143,5	119,2
Total :	466,9	355,0	433,3	335,5	119,2

Geochemistry of thermal waters

Waters of the Bohemian Massif and of the West Carpathians are divided according to Palmer & Gazda's indexes and ranged according to Gazda's classification (Franko, Gazda, & Michaliček, 1975). These authors have distinguished the following types:

- basic (one index > 50 eq. %),
- intermediate (two indexes 33-50 eq. %),

- mixed (one index 33-50, other indexes < 33 eq. % or all indexes < 33 eq. %).

Waters of the Bohemian Massif belong to all three types.

GTW of the spa Karlovy Vary belong to the mixed type $S_1(SO_4)$–A_1–$S_1(Cl)$. They have silicate and sulphate-chloride mineralization. Smejkal & Hladiková (1984) proved the fossil origin of Na^+, SO_4^{2-} and Cl^{-1} in mineral waters of "Karlovy Vary" type, based on a study of S, O, C isotopes in waters and sediments of western Bohemia. In 22 springs of the west Bohemian spas triangle the authors found an extraordinary homogeneity of isotopic composition of sulphur ($\delta^{34}S$ = + 5,3 ± 0,5 ‰) in contrast to considerable inhomogeneity ($\delta^{34}S$ = – 39 to + 31 ‰) in other mineral waters of the Bohemian Massif. The accumulation of sulphates followed the formation of coal seams during the deposition of the Miocene Cypris formation. They formed in an inland sulphate-rich lake. The sulphates are associated with volcanic emissions in the West Bohemian Miocene. GTW of Teplice v Čechách belong to this type of water. Carbonate mineralization (A_2) dominates over chloride. The basic type A_1 is represented by waters of crystalline complexes and of Cretaceous complexes. Waters in Jachymov and in Velké Losiny have silicate mineralization and waters in Ústi n/Labem and in Dečin have hydrosilicate mineralization.

The type A_2 is represented by waters in Jánske Lázně (associated with crystalline complexes and forming in lenses of dolomitic limestones) and in Teplice n/Bečvou (associated with Devonian limestones). They have carbonate mineralization. The basic chemistry is given in Table 5 (Franko & Kolářová, 1983).

Waters of the *West Carpathians* represent several types of water with a mineralization due to water-rock interaction (Franko, Gazda & Michaliček, 1975). The basic types $S_2(SO_4)$ and A_2, the intermediate type A_2-$S_2(SO_4)$ and the mixed type $S_1(Cl)$-$S_2(SO_4)$-A_2, are represented by GTW of Triassic carbonates in intermontane depressions (Table 6) and in the Transdanubian Mid-mountains. They are waters from natural springs (for example Pieštany, Sklené Teplice, Bojnice, Turčianske Teplice) and wells (for example Bešenová and Komárno). These waters have sulphate and carbonate mineralization or intermediate carbonate-sulphate mineralization. The mineralization results from dissolution of Labe- and Middle Triassic ("Keuper") and Early Triassic evaporites (gypsum, anhydrites). For example: the isotopic composition of ^{34}S in GTW of two adjacent localities in Liptovská kotlina basin is different. The isotopic composition of ^{34}S in GTW of the spa Lúčky is + 24,58 ‰ and corresponds to evaporites in the upper part of the Lower Triassic. Isotopic composition of ^{34}S in Keuper evaporites is 15-17 ‰ (GTW in Bešeňová). The mixed type $S_1(Cl)$-$S_2(SO_4)$-A_2 is represented by GTW in Komárno; these are waters mixed in a variable ratio, with chloride and sulphate mineralization. Miocene chloride mineralization waters have seeped into Triassic carbonates.

Waters in Triassic carbonates (wells at Lakšárska N. Ves, Šaštin-Stráže and at Podhájska) also belong to the basic type $S_1(Cl)$ but their genesis is different. Waters from Lakšárska N. Ves (in the Vienna Basin) belong among waters with chloride mineralization. The isotopes of $\delta^{18}O$ and δD indicate their meteoric origin because the values are about –10,9 ‰ or –77 ‰ and in the $\delta D/\delta^{18}O$ diagram they are near to the meteoric water line and not far from the field characterizing the rainfall in the area surrounding Vienna. The waters in Šaštin-Stráže (Vienna Basin) indicate mineralization of marine origin and are degraded by vertical and horizontal infiltration (Remšik,

Table 5: Chemistry of GTW in the Bohemian Massif.

Locality	Aquifer (age)	pH	T (°C)	T.D.S. (g/l)	Na^+ (mg/l)	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_2	H_2S	Type of water (Palmer & Gazda index)
Karlovy Vary	granite (Paleozoic)	6,9	52,1	6,5	1713	98,0	37,3	135,9	607,7	1639	2163	--	--	$S_1(SO_4)$-A_1-$S_1(Cl)$ 39-29-20
Jáchymov	granitiods, mica schists, phyllites (Cambrian, Paleozoic)	8,1	34,2	0,7	144,7	11,1	4,4	17,0	7,2	15,2	390,5	--	--	A_1 77
Jánske Lázne	phyllites, limestone (Paleozoic)	7,1	27,5	0,3	21,5	4,1	11,6	43,9	3,5	7,4	228,8	--	--	A_2 60
Velké Losiny	migmatites (Proterozoic)	--	30,5	0,2	67,5	1,8	0,61	3,0	12,8	21,4	43,1	--	1,0-4,6	A_1 64
Teplice v Čechách	quartz porphyry (Paleozoic)	6,8	39	1,0	231,8	11,9	9,5	43,0	50,1	125,4	560,0	--	--	A_1-A_2-$S_1(SO_4)$ 49-22-19
Ûsti n/Labem	sandstones (Lower Turonian)	7,35	28,5	2,0	515	27,5	8,1	31,1	118,4	254,7	1025	--	--	A_1 57
Dečin	sandstones (Cenomanian)	--	32,7	2,2	600	18,3	3,6	14,0	137,2	216,9	1171	--	--	A_1 66
Teplice n/Bečvou	limestones (Devonian)	6,2	22,0	2,6	71,2	11,5	48,6	490,6	39,4	9,5	1879	2563	--	A_2 89

Table 6: Chemistry of GTW in the West Carpathians.

Locality	Aquifer (age)	pH	T (°C)	T.D.S. (g/l)	Na^+ (mg/l)	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_2	H_2S	Type of water (Palmer & Gazda index)
Piešťany	dolomite, limestones (Triassic)	6,7	67,2	1,4	90,9	15,9	41,3	228,5	118,7	558,4	340,1	151,0	12	$S_2(SO_4)$ 55,3
Sklené	ditto	6,3	52,5	2,5	22,6	11,4	107,0	525,0	2,6	1484	335,5	288,0	--	$S_2(SO_4)$ 81,0
Bojnice	ditto	6,7	48,0	0,67	17,6	5,2	32,8	102,2	3,6	81,9	414,8	89,4	--	A_2 78,4
Turčian Teplice	ditto	6,7	44,5	1,46	44,2	11,3	61,6	255,5	3,57	488,0	576,4	200,2	0,0	A_2-$S_2(SO_4)$ 48,0-39,6
Komárno vrt M-3	ditto	6,5	50,0	2,91	380	33,6	90,8	350,1	557,6	826,3	616,3	245,9	0,0	$S_1(Cl)$-$S_2(SO_4)$-A_2 36,5-35,4-21,8
Bešeňová	ditto	6,4	61,5	3,0	30,0	22,0	199,4	495,0	9,0	1558	683,2	647,0	0,0	$S_2(SO_4)$ 69,0
Lakšár N. Ves vrt RGL-1	ditto	6,55	77,4	6,8	1600	66,0	120,0	500,0	2280	1370	744,4	220,0	135,0	$S_1(Cl)$-$S_2(SO_4)$ 59,6-19,0
Šaštin-Stráže vrt RGL-2	ditto	7,30	56,0	10,9	3688	70,0	26,1	107,2	3813	1321	1479	--	100,0	$S_1(Cl)$-$S_1(SO_4)$ 63,5-16,2
Podhájska vrt PO-1	ditto	6,6	82,0	18,5	5973	373	106,4	461,6	9394	772,6	1159	317,0	--	$S_1(Cl)$ 86
Topoľníky FGT-1	sands (Pontian)	7,80	73,0	1,9	540	6,0	1,2	6,0	113,4	22,2	1208	30,9	0,0	A_1 82,7
Dunajská Streda DS-1	ditto	8,3	90,0	7,3	2440	64,0	2,7	22,0	2542	44,0	2165	158,4	--	$S_1(Cl)$ 66,4

et al., 1989). The isotopic composition of waters in Podhájska ($\delta^{18}O$ = –6,63 to –6,9 ‰ and δD = – 48,2 ‰) shows that in contrast to meteoric waters, these waters are enriched with oxygen and deuterium and thus include a remarkable proportion of inflow of mineralization from marine origin (Franko & Bodiš, 1989). They are the waters of the Levice block in the Danube Basin. Waters of the basic type S_1(Cl) in Triassic carbonates of analogous genesis are not only in the Vienna and Danube Basins but also in the Košická kotlina basin and in the southeastern part of Humenský chrbát.

The basic types A_1 and S_1(Cl) and the intermediate type are represented by waters of the Central Depression of the Danube Basin (Pannonian Basin). In the depression the mineralization and chloride content increase with depth, the carbonate content decreases and the value of the $rHCO_3$ (rCl) (Franko, *et al.*, 1989) coefficient decreases proportionally. $\delta^{18}O$ (Figure 4) is in accordance with this trend. Its value decreases with depth from –13,18 ‰ (700-800 m) to –7,31 ‰ (2000-2500 m). These data are evidence for the gradual desalination of the deposition area. At present the original waters of marine origin are replaced by meteoric waters to an approximate depth of 1500 m on the periphery and 2000 m in the centre. This is demonstrated by the content of $\delta^{18}O$ in water of the Danube River which ranges from –11,0 to –13,5 ‰ (Franko & Bodiš, 1989). Such waters are distributed in Tertiary sediments of the entire Inner West Carpathians. With respect to the exploitation of GE and existing information, only two structures (Horné Strháre - Trench graben) in the South Slovak basin, and Beša-Čičarovce in the East Slovak basin are potential prospects.

DESCRIPTION OF THERMAL WATER WELLS

Location

In the Bohemian Massif only one potential area for exploitation of GE has been identified (Figure 5). In České středohoří Mts. the GTW are associated with Cenomanian and Middle Turonian sandstones. So far no geothermal wells have been drilled in this area.

In *the West Carpathian Mts.* (Figure 5) 25 potential areas have been defined for the exploitation of GE (Franko, 1980). Geothermal wells have only been drilled in the Komárno elevated block (4), in the central depression of the Danube basin (30), Vienna basin (2), Topoľčany bay (1), Bánovská kotlina depression (1), Levice block (2), Liptovská kotlina basin (2) and Levočská panva basin (2). In the years 1971-1988 44 wells were drilled.

Characteristics of wells

Geothermal wells are drilled by the Rotary system (Romanian rig 2DH-75, F-100), using clay drilling mud; some intervals are cored. The depth of the wells ranges from 1000-2800 m (in one case 210 m). Cemented casing in Neogene sands is opened by jet perforation. In Triassic carbonates a filter with a slotted liner is used. Intervals above the aquifer are cemented. Production casing has a diameter of 7 inches. GTW are generally exploited by free flow, but in three cases deep well pumps have been used. Data from selected wells and aquifers are given in Table 7.

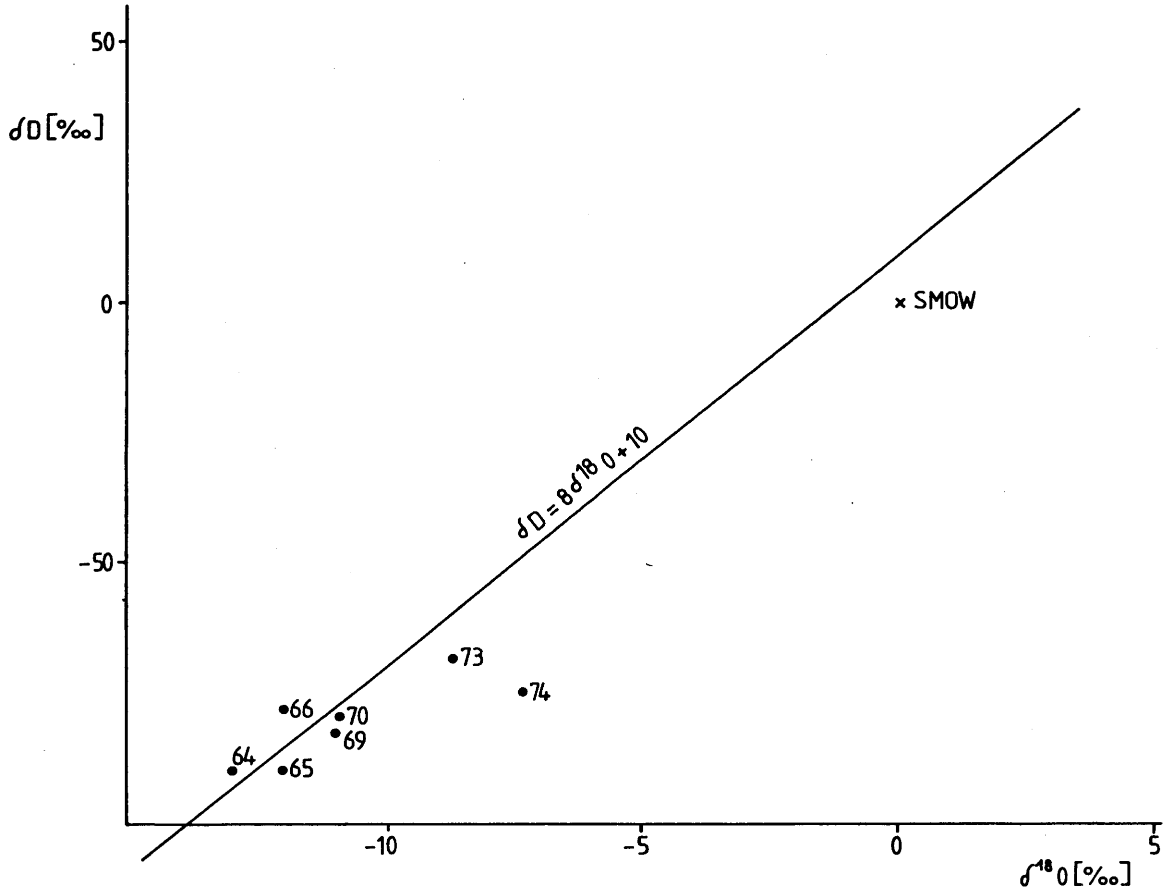

Figure 4: **$\delta D/\delta^{18}O$ ratios in some GTW of the central depression of the Danube basin.**

No. of locality / drillhole: **64** - Diakovce (Di-1); **65** - Topoľníky (FGT-1); **66** - Králová pri Senci (FGS-1/A); **69** - Chorvátsky Grob (FGB-1/A); **70** - Galanta (FGG-1); **73** - Čalovo (Č-1); **74** - Dunajská Streda (DS).

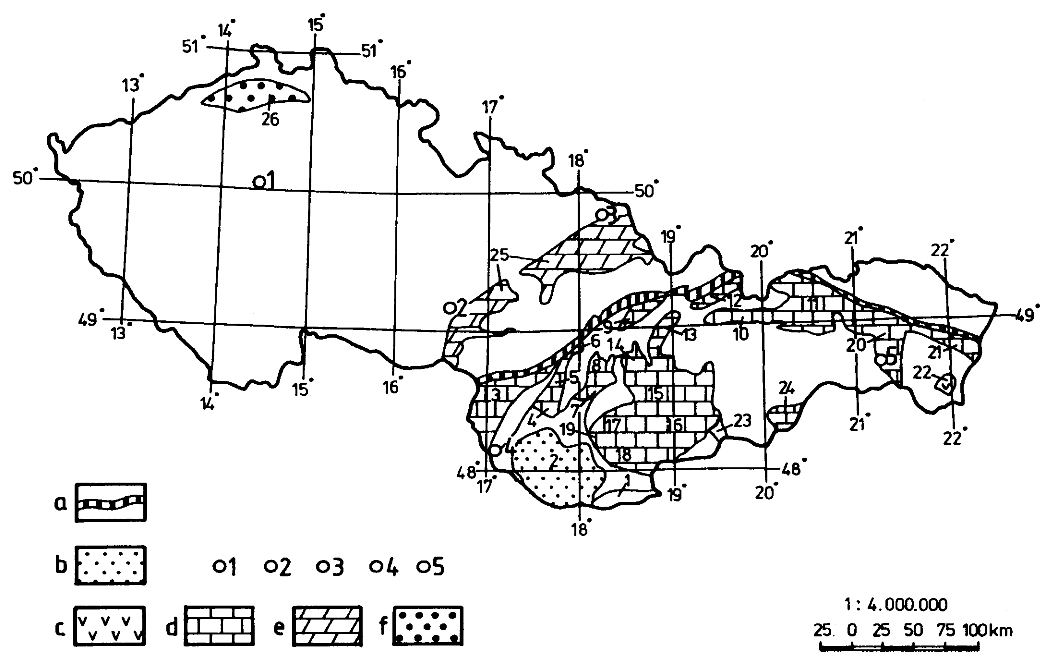

Figure 5: Map of prospective areas of geothermal resources in Czechoslovakia (Franko, 1989).

Legend: **(a)** - Klippen Belt; **(b)** - Neogene sands; **(c)** - Neogene andesites and their pyroclastic products; **(d)** - Mesozoic dolomites, limestones, quartzites; **(e)** - Mesozoic-Paleozoic limestones, dolomites; **(f)** - Cretaceous clastics; **(1)** - Komárno elevated block; **(2)** -Central depression; **(3)** - Vienna basin; **(4)** - Trnava bay; **(5)** - Pieštany bay; **(6)** Trenčianska kotlina (depression); **(7)** - Topoľčany bay; **(8)** - Bánovská kotlina (depression); **(9)** - Žilinská kotlina (depression); **(10)** - Liptovská kotlina (depression); **(11)** - Levoča basin; **(12)** - Skorušina basin; **(13)** - Turčianska kotlina (depression); **(14)** - Hornonitrianska kotlina (depression); **(15)** - Central Slovakian neovolcanic rocks (NW part); **(16)** - Central Slovakian neovolcanic rocks (SE part); **(17)** - Zlaté Moravce bay; **(18)** - Levice block; **(19)** - Nitriansky chrbát (ridge); **(20)** - Košická kotlina (depression); **(21)** - Humenský chrbát (ridge); **(22)** - Beša-Čičarovce structure; **(23)** - Horné Strháre-Trenč graben; **(24)** - Rimavská kotlina (depression); **(25)** - Carpathian Foredeep; **(26)** - Bohemian Mid-Mountains.

Towns: **1** - Praha; **2** - Brno; **3** - Ostrava; **4** - Bratislava; **5** - Košice.

Table 7: Hydrogeothermal data from wells.

Locality well	Year	Depth of well (m)	Open segment from - to (m)	Collector thickness (m)	Age Lithology of collectors	Draw-down (Δp) (MPa)	Outflow (l/s) Temperature (°C)	Coeff. of transmissivity T (m^2/s)	Heat [1] power P_t(MW)	Utilization
Dunajská Streda	1971	2500	2432-2183	56	Pontian sands	0,511	15,6 91,5	$3{,}9.10^{-4}$	4,99	Glasshouses, buildings
Topolniky FGT-1	1974-75	2501	2487-1394	140	Pontian sands	0,245	21,3 74,0	$1{,}6.10^{-3}$	5,26	Glasshouses, sports hall, swimming pools
Horná Potôň FGHP-1	1977-78	2500	1806-1394	53	Pontian sands	0,202	18,3 68,0	$1{,}2.10^{-3}$	4,06	Glasshouses
Gabčikovo FGGa-1	1981-82	2582	1879-1146	117	Pontian sands	0,147	10,2 52,0	$1{,}4.10^{-3}$	1,58	Swimming pools
Galanta FGG-2	1982-83	2100	2032-1706	92	Pannonian sands	0,241	23,3 80,0	$2{,}6.10^{-3}$	6,34	Housing quarters, hospital, pensioners' houses
Podhájska Po-1	1973	1900	1740-1170	310	Triassic dolomites, limestones	1,378	41,6 80,0	$1{,}5.10^{-4}$	11,32	Glasshouses, buildings, swimming pools

[1] $P_t = Q \, . \, \Delta t \, . \, C \, . \, 10^{-3}$ (MW); Q = outflow (l/s); Δt = difference between surface and reference temperature (15°C); C = specific heat capacity of water (4,186 J/kg/K).

Table 7: Hydrogeothermal data from wells (continued).

Locality well	Year	Depth of well (m)	Open segment from - to (m)	Collector thickness (m)	Age Lithology of collectors	Draw-down (Δp) (MPa)	Outflow (l/s) Temperature (°C)	Coeff. of transmissivity T (m^2/s)	Heat [1] power P_t(MW)	Utilization
Komárno M-3	1975-76	1184	1139-1184	11	Jurassic, Triassic limestones, dolomites	0,130	5,3 49,0	$1,19.10^{-4}$	0,75	Swimming pools
Šaštin-Stráže RGL-2	1982-83	2605	2570-2005	120	Triassic dolomites, limestones	2,196	12,0 73,0	$2,6.10^{-4}$	2,91	Conserved
Lakšárska Nova Ves RGL-1	1983-84	2100	2065-1242	92	Triassic dolomites, limestones	0,650	24,3 78,0	$2,5.10^{-3}$	6,41	Conserved
Bešeňová ZGL-1	1986-87	1987	1987-1420	135	Triassic dolomites, limestones	1,349	30,0 62,0	$1,1.10^{-4}$	5,90	Buildings, swimming pools

[1] $P_t = Q . \Delta t . C . 10^{-3}$ (MW); Q = outflow (l/s); Δt = difference between surface and reference temperature (15°C); C = specific heat capacity of water (4,186 J/kg/K).

Table 8: Some geochemical and technical data.

Locality well	Aquifer temperature (°C)	pH	T.D.S. (g/l)	Chemical type of water; Palmer & Gazda's index	Saturation state Calcite	Dolomite	Gypsum	Type of gases; acid/ nonacid	Gas/water ratio	Bubble point (m)
Dunajská Streda DS-1	92,0	8,3	7,02	basic; $S_1(Cl)$	0,176	0,400	--	CO_2 CH_4, N_2	0,327	577,4
Topołniky FGT-1	79,0	7,8	1,95	basic; A_1	–0,383	–0,416	--	CO_2 N_2, CH_4	0,011	32,6
Horná Potôň FGHP-1	68,0	8,3	4,70	basic; $S_1(Cl)$	0,549	1,160	--	CO_2 CH_4, N_2	0,010	277,2
Gabčikovo FGGa-1	60,5	8,0	1,00	basic; A_1	0,287	0,793	--	CO_2 CH_4, N_2	0,013	29,3
Galanta FGG-2	80,0	7,6	4,90	basic; A_1	–0,374	–0,021	--	CO_2 NH_4, N_2	0,049	28,4
Podhájska Po-1	95,0	7,65	18,83	basic; $S_1(Cl)$	1,969	3,433	–0,760	CO_2 N_2	2,693	402,0
Komárno M-3	55,0	6,6	3,10	mixed; $S_2(SO_4)$ -$S_1(Cl)$-A_2	0,333	0,695	–0,342	CO_2 N_2	0,320	≈ 130
Šaštin-Stráže RGL-2	73,0	7,9	10,90	basic; $S_1(Cl)$	1,453	2,793	–1,077	CO_2, H_2S CH_4, N_2	0,607	≈ 60
Lakšárska N. Ves RGL-1	78,0	6,6	6,84	basic; $S_1(Cl)$	0,663	1,055	–0,299	CO_2, H_2S CH_4, N_2	0,533	111,3
Bešeňová ZGL-1	67	6,4	2,90	basic; $S_2(SO_4)$	0,518	1,005	–0,175	CO_2	1,118	162,0

Note : Saturation state calculated by PCWATEQ.

Characteristics of thermal waters

Data concerning thermal waters from selected wells are given in Table 8. Chemical data are described in an earlier section.

Present use of thermal water and prospects for development

GTW are exploited at 33 localities and the total discharge of these resources is about 555 l/s; the utilizable power is about 74 MW. The divisions of the localities according to water temperature are (Table 9):

Table 9: Exploitation of GTW.

Number of localities	Surface temperature of source (°C)	Total yield (l/s)	Power (P_t)
13	15-30	180	7,2
16	30-70	277	40,8
4	70-100	98	26,0
Exploitation for one purpose :			
23	--	345	30,8
Exploitation for more purposes :			
10	--	201	43,2

GTW are mainly utilized in agriculture for heating glasshouses, plastic houses and for heating the soil (about 15-20 hectares), at about 10 localities for heating three social farm buildings, a sports hall, one case in the fish rearing industry, one case for growing mushrooms, and for swimming pools of total water area of about 55,000 m^2. In Galanta they intend to heat a housing quarter with 1100 flats, a hospital and a home for pensioners.

Of the 26 potential areas in Czechoslovakia, three have been explored in Slovakia, four are being investigated and a further six being are prepared for exploration. In Slovakia medium temperature resources (t = 100-150°C) are associated with nine areas, high temperature resources (t > 150°C) are associated with three areas, and low temperature resources (t = 15-100°C) are associated with all 26 areas. On the basis of the evaluation of heat energy potential (HEP), prospective, prognostic and verified by well, about 590 MW comes from resources (exploitation by individual wells) and about 3860 MW comes from reserves (exploitation with re-injection: the cold front reaches production wells in about 40 years). The average rate of drilling is three wells per year - one is exploratory, and two are exploratory-exploitation wells. It is probable that this trend will continue.

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THE HYDROGEOTHERMAL SYSTEMS IN HUNGARY

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INTRODUCTION

Hungary has more than 100 years experience of thermal water exploration, development and exploitation and a tradition over about 50 years of multipurpose thermal water utilization. A considerable amount of low enthalpy geothermal energy resources occurs in the sedimentary formations of the intermontane Carpathian basin. This sedimentary basin belongs to the passive geothermal system. The average reciprocal geothermal gradient amounts to 18 m/°C; that is, the temperature gradient is 50-60 °C/km, which is twice the normal global value.

Thermal water, as well as geothermal energy development and utilization, was always directed, governed and sponsored by the Hungarian state by legal and institutional measures. These measures involve specific laws, regulations, general technical and financial assistance, funding support, loans, grants, risk coverage, tax and fee exemptions, applied research, etc.

MAIN CHARACTERISTICS OF HYDROGEOTHERMAL SYSTEMS IN HUNGARY

Main features of the geological setting

Crustal structure: Recent geophysical and geothermal investigations have indicated that a close relationship exists between the structure of the crust and the evolution of the Pannonian basin. Deep refraction and reflection seismic measurements have revealed that the intermontane Pannonian basin has a relatively thin crust, that is, the Mohorovicic-discontinuity is situated at an average depth of 24 to 25 km. Because of this thin crust the asthenosphere is relatively close to the surface. The lithosphere-asthenosphere boundary is believed to be at a depth of about 55 to 60 km. The thinning-out of the crust and the updoming of the asthenosphere was the result of a complicated sub-crustal magmatic process, closely related to the Alpine orogeny during the Neogene (Dövényi, *et al.*, 1983).

Principal geological units of Hungary: The Hungarian basin consists of three major geological units:

1. Precambrian and Paleozoic basement with rigid, highly deformed, metamorphic, crystalline rocks representing the framework and infrastructure of the basin. Only locally

in its carbonate members are some aquifer systems developed (e.g. a Devonian dolomite aquifer at Bük in west-Hungary).

2. A superimposed Mesozoic basement composed mainly of thick and extended limestone, dolomite and marlstone formations including considerable karstic and fissure water resources. The Mesozoic sedimentation took place in a geosyncline stretching from SW to NE, representing a continuation of the Alpine trough. A vast and thick carbonate rock sequence, consisting mainly of Triassic dolomite and limestone was formed. Its total thickness is about 5000 to 6000 metres. The rigid, brittle carbonate mass reacted to later tectonic movements mainly in the form of fractures and fissures. Major faults of SW-NE and SE-NW strike developed.

3. Neogene clastic rock sequences involving several hydro-stratigraphic horizons with formation waters. This vast sedimentary column represents the superstructure of the Pannonian intermontane region. The Alpine orogenic movements triggered off a general subsidence of epeirogenic character within the Hungarian median block. Due to this subsidence many sub-basins of different shapes and depths were formed. This is responsible for the compartmentalization of the aquifers. The subsidence started in the early Tertiary and reached its paroxysm in the Pliocene, resulting in a vast sedimentary sequence up to 5000 m thick (Rybach & Muffler, 1981).

Hydrogeology and origin of thermal waters

Among the three basic geological units only two are regionally important as thermal water-bearing systems, namely (Figure 1):

- Mesozoic, mainly the Triassic fractured-fissured-karstified carbonate rock complex, and
- Neogene, mainly Middle-Pliocene (Upper Pannonian) clastic, porous formations.

Besides these two groups there are other thermal water-bearing formations, ranging in age from the Devonian to the Quaternary, scattered throughout the country, but they have only local or minor importance and occurrence.

Mesozoic, mainly Triassic fractured rock complex: This brittle, rigid and heavily fractured-fissured-jointed and, on its upper part, karstified carbonate rock complex includes many reservoir forming elements, such as fractures, joints, openings and caverns. The upper part of the carbonate rock mass is intensively karstified, not only at its outcrops, but also where it is buried (paleokarst). Besides the general fractured-jointed pattern of the carbonate rock complex, there are many major faults and fracture lines of great hydrogeological importance. Numerous natural thermal springs are ascending to the surface along such major faults, as for example along the Buda Thermal Line on the right bank of the Danube in Budapest.

The Triassic carbonate formation is characterized by secondary "carbonate" porosity and by fractured permeability. The tectonic and karstic elements forming the conduits and flow paths have a controlling effect on the thermal water movement. It is well known that thermal water-yielding capacity of wells completed in carbonate rocks varies primarily with the density

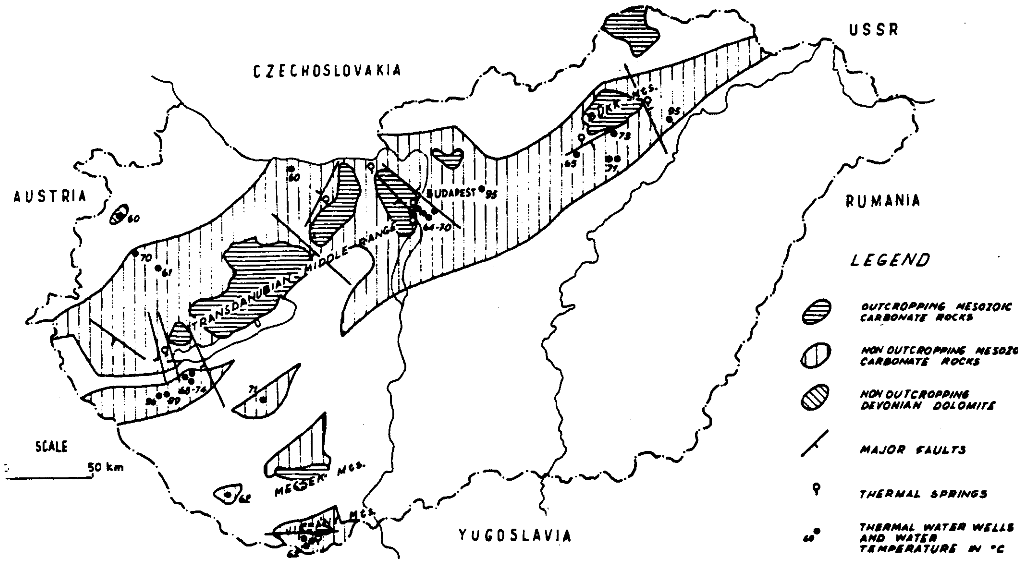

Figure 1: Thermal water wells and springs issuing from the fractured basement rocks in Hungary.

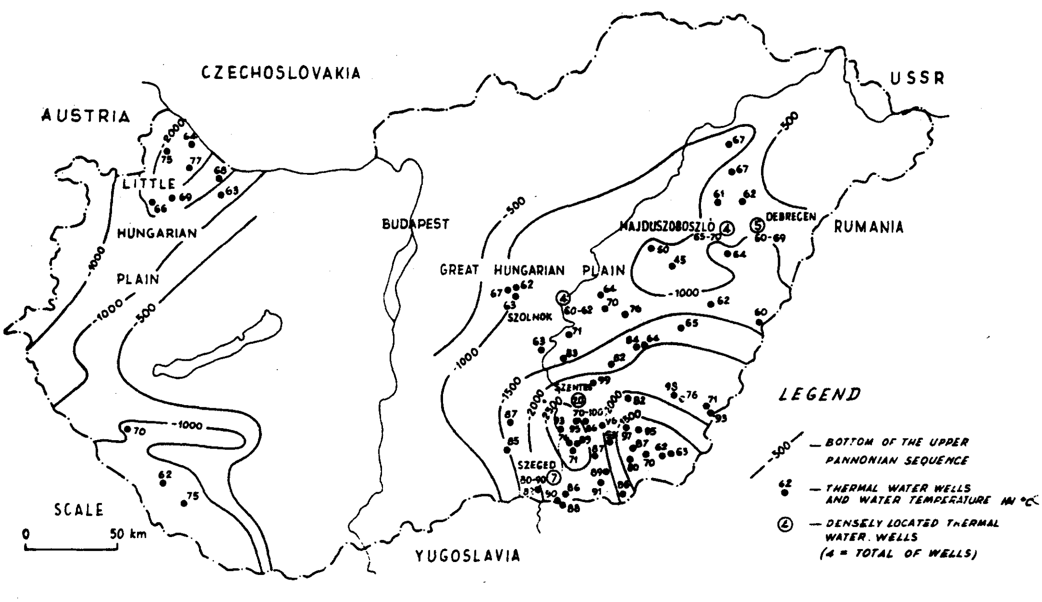

Figure 2: Thermal water wells producing from Upper Pannonian aquifers in Hungary.

and size of the fractures, joints and openings that are penetrated. The discharge of thermal water wells varies within a wide range and may occasionally be very high; even 25,000 litres per minute has occurred in Budapest. Thermal water wells located in carbonate rocks often have a sustained water yield. There are some wells more then 100 years old and this means that the reservoir is continuously recharged. An eventual decrease in the flow rate can usually be attributed to an ageing and deterioration of the well structure or to scaling. Recently, large withdrawals of karstic water by the mining industry in the Trans-Danubian Middle Range has had a harmful effect on the thermal water resources.

Nevertheless, there are many deep-seated, deeply buried aquifers within the carbonate rock mass which are totally isolated and have no communication with meteoric waters and as a result they are not currently being recharged. These thermal waters have a high total dissolved solid content and a high reservoir temperature, as well as an out-flow temperature up to nearly 100°C.

The geothermal conditions in carbonate rocks often range between extreme positions. Descending cold meteoric water and ascending hot water exert an opposite effect on the rock temperature causing quite different conditions. The entire carbonate system has an unusual thermodynamic character and, as a result, the hydraulically governed flow of geothermal water is in the form of convective cells.

Thermal waters within carbonate reservoirs are generally calcium-magnesium bicarbonate waters of various concentrations. In the near-surface environment the hydrological cycle exerts a decisive influence on the water budget as well as upon the water chemistry of the fractured aquifers. In the deeper portions of the carbonate rock complex however, flow, exchange and mixing with meteoric water generally takes place slowly.

Carbonate basement rocks and the overlying younger fractured sedimentary formations must at some point form a common reservoir system, forming a composite bedrock aquifer with an interconnected fracture network allowing constant communication throughout (e.g. the Eocene marlstone formation with underlying Triassic dolomite in Budapest, and the Upper Pannonian silicified, fractured sandstone with underlying Triassic dolomite in Héviz, represent such a complex aquifer system).

Upper Pannonian (Middle Pliocene) porous thermal water reservoir system - a regional system: In the Pannonian sedimentary basin, which consists of several sub-basins, superimposed composite sand and sandstone layers alternate with clay, clayey marl, marl and siltstone. Accordingly, a sequence of aquifers, semi-aquifers, aquitards and aquicludes were developed as a consequence of lacustrine, fluviatile and semi-deltaic sedimentation in the Pliocene. The spatial distribution and geometry of the sand and sandstone units are defined by the general character and pattern of the repetitive sedimentary sequence.

The Upper Pannonian sedimentary column includes the most important thermal water reservoir system in Hungary (Figure 2) as well as in the contiguous basin areas of neighbouring countries (former Czechoslovakia and Yugoslavia, Rumania). It represents a multi-layer, multi-unit or multiple reservoir system. The aquifers are 500 to 2500 m deep and contain mainly static-stagnant formation waters which are completely sealed and excluded from the hydrological cycle and are not recharged. Within these horizontal and sub-horizontal sandy deposits the reservoir pressure is everywhere equal or near to the hydrostatic value. The base or reservoir temperature varies from 30 to 140°C. The highest well-head temperature of the producing wells is about 100°C. The total dissolved solid content of the water ranges from 1 to 6 gram/litre and is predominantly of an alkaline bicarbonate character. In some aquifers there is a considerable gas content dissolved in the water (both CO_2 and CH_4). This gas is an important source of reservoir pressure which is now slowly reducing and resulting in some difficult problems with regard to the production process for the thermal water. Consequently, in many thermal water fields natural outflow from the thermal wells is no longer possible and pumps have to be installed. The initial flow rate of the thermal water wells ranged from a few hundred to 3000 litres per minute. At the same time the initial static well-head pressure was about 4 to 5 bars.

The Upper Pannonian multiple reservoir system contains the greatest thermal water resource in Hungary. About 55 to 70 percent of all thermal wells tap this formation.

Local thermal water reservoir systems of limited extent: Within the Paleozoic - Precambrian crystalline basement in west Hungary, a Devonian fractured-fissured dolomite of limited extent lies at a depth of about 1000-1300 m and contains thermal water resources that are important for balneology.

In many parts of the country littoral and sub-littoral Helvetian, Tortonian and Lower-Pannonian conglomerates, breccias and limestones form thermal water reservoirs.

In the deepest portion of the Neogene (mainly Miocene) sedimentary column and in the underlying Mesozoic basement some geopressured aquifers occur. A noteworthy example is the high-enthalpy geothermal resource recently discovered by an exploratory oil borehole in the southern part of the Great Hungarian Plain, at Fábiánse-bestyén near the city of Szentes. After penetrating Upper and Middle Triassic formations, at a depth of 4239 m in Lower Triassic strata, a blowout occurred which was accompanied by the production of saline thermal water and steam at a well-head temperature of 160°C. Unfortunately, the borehole had to be abandoned because of technical difficulties before it could be completed and tested.

As a result of continuous subsidence in Upper Pliocene and Quaternary times, a thick sedimentary column formed in South and SE-Hungary where sand and gravel deposits up to 800 and 1200 m thick, respectively, contain thermal water resources with well-head temperatures of 30 to 55°C.

Estimation of thermal water reserves: The volume of thermal water in place was measured from the volume of the pore space, calculated from core analysis and electric logs of the wells; that is, the volumetric method of estimating thermal water reserves was applied.

The thermal water reserves were estimated to be 2500 km^3. The majority of these reserves is within the multi-unit sand-sandstone aquifer system of the Neogene. Only 50 km^3 are assumed to be in the fractured carbonate rocks of mainly Triassic age. The geothermal energy resource is believed to be $5{,}73 \times 10^{17}$ kJ (Table 1), and the actual recent thermal water yield is estimated to total 500,000 m^3/d.

Table 1: Estimation of thermal water resources in Hungary.

Temp. of out flowing water	Format-ion temp.	Depth - interval	Area	Stored water resource	Stored heat resource	Actual water production	Heat capacity	Cumulative water production Total	Cumulative water production From the stored resource	Pressure decrease
°C	°C	m-m	$10^3.km^2$	$10^3.km^2$	$10^{15}.kJ$	$10^3.m^3/d$	MW	km^3	km^3	bar
30-40	35-48	400-650	70	0,7	92	200	303	1,0	0,3	--
- 50	- 60	- 900	50	0,5	92	85	170	0,4	0,2	--
- 60	- 73	- 1200	40	0,5	117	60	162	0,3	0,2	--
- 70	- 85	- 1500	50	0,3	86	55	182	0,3	0,1	--
- 80	- 98	- 1800	25	0,2	68	35	138	0,2	0,1	--
- 90	- 110	- 2100	20	0,2	78	35	158	0,2	0,2	--
- 100	- 123	- 2400	15	0,1	40	30	138	0,2	0,2	--
				2,5	573	500	1250	2,6	1,3	calculated : 2,6 measured : 1-2

(Compiled by Liebe, 1989).

Due to the production of thermal water and intensive use of the geothermal energy, the reservoir energy is slowly dissipating from the porous, confined aquifers, and as a result the reservoir pressure has decreased by 1 to 5 bars. Consequently, the natural flow of the thermal wells has stopped and these wells have to be pumped.

Hydrochemical features of thermal waters

Thermal waters within the Upper Pannonian multiple reservoir systems are generally of the alkaline bicarbonate type, with 2 to 4 gram/litre as an average total dissolved solid content. The chloride ion content is generally less than 100 milligrams per litre.

Thermal waters of the Mesozoic carbonate rock formation are predominantly of the calcium-magnesium bicarbonate type with a variable concentration. A close relationship exists between the depth of the fractured reservoir system and the concentration. The chemical composition of these waters is highly influenced by the hydrodynamic phenomena. Mixing of different kinds of water is a common feature.

The hydrochemical pattern of Miocene thermal waters is highly variable. Some are of meteoric origin, but there are numerous examples of connate or fossil waters, especially in basin areas at great depths.

Geothermal features

The Hungarian or so called Pannonian basin, surrounded by the Carpathians, Alps and Dinarides, has a particular and unique position in the field of geothermics. Although this intermontane basin is not situated within a primary geothermal area, such as a zone of an active volcanic belt or other near-surface igneous activity, it nevertheless displays a conspicuous regional, positive geothermal anomaly. The last volcanic activity in the Carpathian basin was in late Pliocene and early Quaternary times and took the form of limited basaltic flows.

The lithosphere of the Pannonian basin is characterized by a high heat flow of about 90 to 112 mW/m^2 (Figure 3). The mean temperature at a depth of 1 km is about 70°C, at 2 km about 120°C, at 3 km about 165°C and, according to the most recent data, in certain places more than 200°C at 4 km. It is believed that the main mechanism by which terrestrial heat is transferred from the asthenosphere is by conduction and, therefore, the Pannonian basin represents a conductive geothermal system.

It can be concluded that the geothermal conditions in the Carpathian basin are primarily determined by a particular crustal structure and magma-kinetic processes taking place within the crust and upper mantle. The thermal history of the basin is related to phenomena that occurred in the Neogene. Geothermal conditions are secondarily controlled by the geologic setting, hydrogeologic factors, tectonics, and the general evolution of the basin, including sedimentation and compaction (Stegena, *et al.*, 1975).

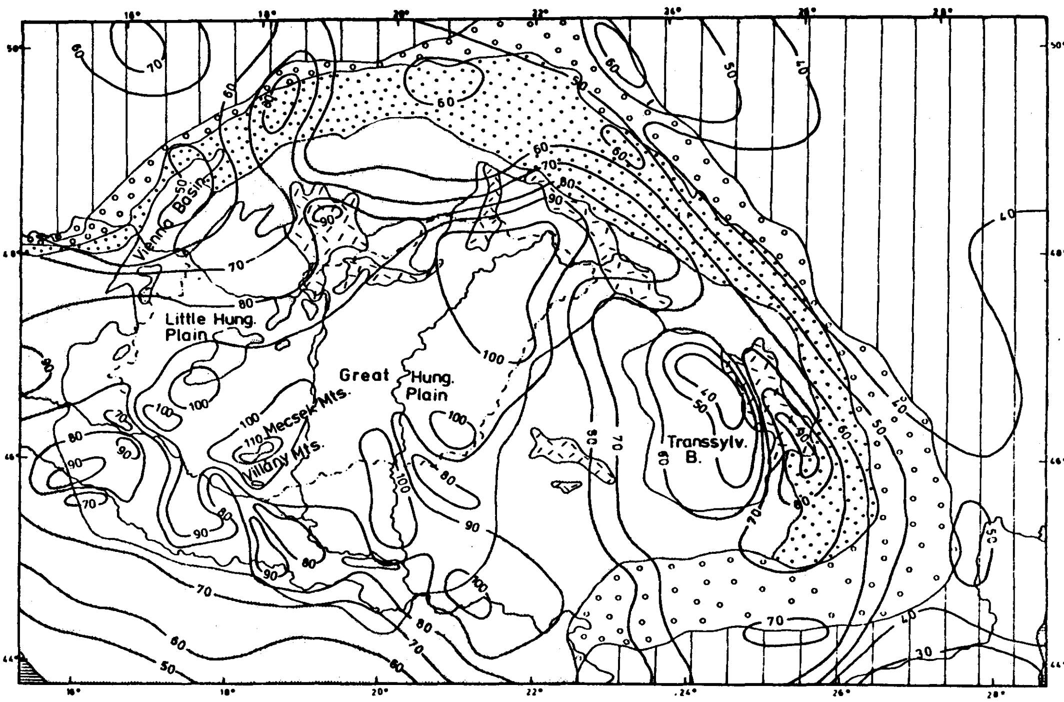

Figure 3: Isolines of heat flow in mW/m^2 units for the Carpatho-Pannonian area and its surroundings (modified from Čermák & Hurtig, 1979).

THERMAL WATER DEVELOPMENT IN HUNGARY : WELLS, PRODUCTION AND USE

Thermal water wells

Currently, there is a total of 1050 thermal water wells in Hungary yielding water at a well-head temperature of more than 30°C. The majority of these wells is in operation, but a limited number have been abandoned or shut down. About 70 percent of the operating wells are located on the Upper Pannonian regional, multiple, thermal, water reservoir system with about 20 percent in the regional, Triassic carbonate aquifer system, and the remaining 10 percent in local, small reservoirs scattered in various parts of the country.

The first thermal water well (with a total depth of 37,5 m) was drilled and completed in Harkány (south Hungary) in 1866. In the next year, in the Margareth Island of Budapest, a 118 m deep well was completed and between 1868 and 1878 another thermal well was drilled to a total depth of 970 m in the City Park of Budapest. All three wells were directed and completed by the famous Hungarian mining engineer end geologist, V. Zsigmondy. After this pioneer era of drilling for thermal water, considerable development of thermal water was carried out in the period between the two world wars and later in the years from 1958 to 1972.

During the exploration for and exploitation of the thermal water a great amount of data was obtained in the fields of geology, hydrogeology, hydrochemistry, hydrodynamics and geothermics. On the basis of these data a systematic scientific evaluation and interpretation of the data was carried out by the Research Center of Water Resource Development (VITUKI) in Budapest and the results were published in five separate volumes between 1965 and 1985. All important technical, geological, hydrogeological, hydrodynamical, hydrochemical and geothermal data were listed in tabulated form with specific references to the present state of wells and to the mode of thermal water utilization of each well. Besides texts and tables several maps, geologic sections, well and electrical logs illustrate each volume (VITUKI, 1986; Figure 4).

Thermal water wells in Hungary are designed and completed according to the geologic environment of the thermal water-bearing horizons (Boldizsár & Korim, 1975). In the Upper Pannonian formation (Figure 5) the so called multiple production wells were drilled in three ways: (a) screened wells; (b) jet-perforated wells and (c) pre-perforated liner completion without grout. In the Triassic fractured-jointed-karstified formation an open hole completion is practical (d).

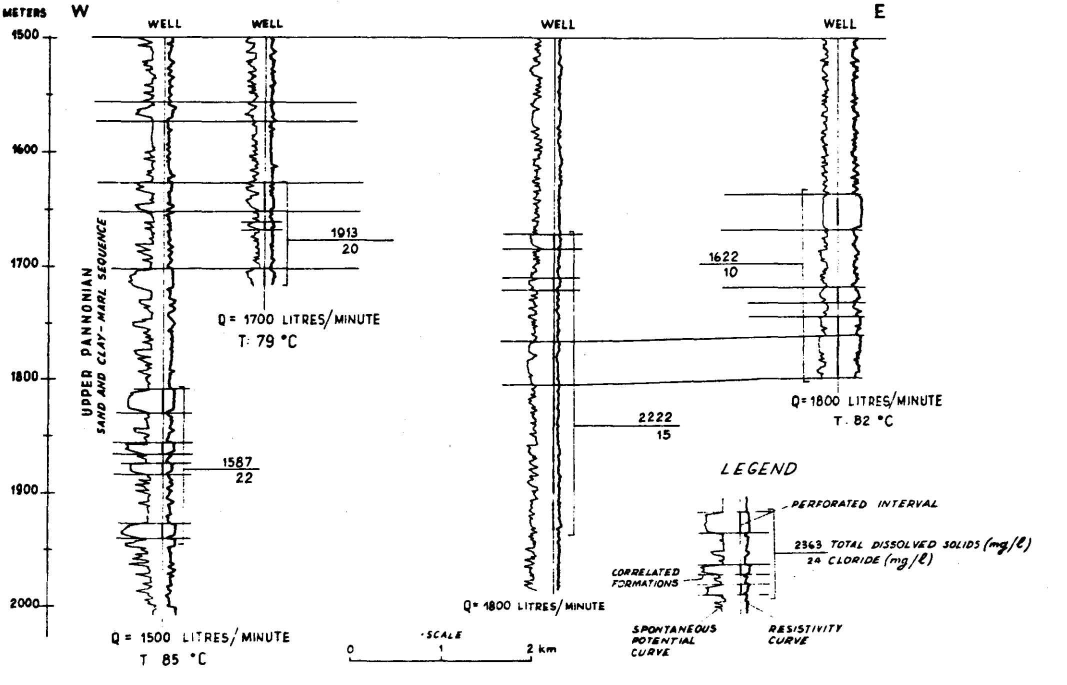

Figure 4: Example of a multi-unit reservoir in the surroundings of Szentes.

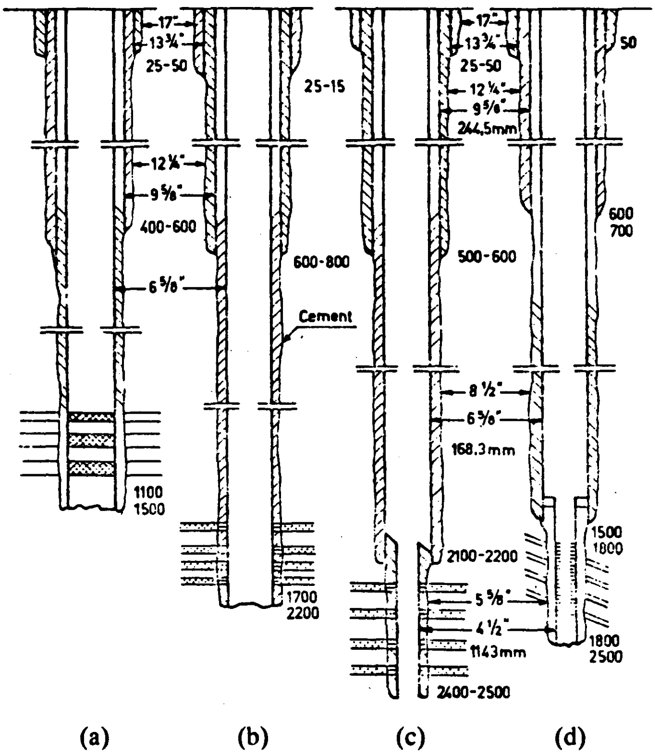

Figure 5: The main types of thermal water wells completed in the Pannonian basin.

The thermal water production history of the wells and the reservoir performance depends upon the aquifer system that is penetrated and tapped (for example unconfined, confined, or artesian), on the reservoir energy resources (mainly dissolved gas content) and on the general hydrodynamic conditions. In the City Park of Budapest Well No.2 was drilled and completed in 1938 with an initial water yield of 3200 litres per minute. After 50 years of continuous water production, the present yield remains the same and this is attributed to an active recharge of the carbonate aquifer. On the contrary, in the thermal water field around Szentes a total of 29 thermal wells are currently operating. The cumulative thermal water production amounts to about 140 million m^3 from the confined multi-unit reservoir system. The vast withdrawal of thermal water resulted in an increased rate of depletion of the reservoir energy (mainly dissipation of the dissolved gas content). As a consequence, the thermal water yielding capacity steadily diminished and nowadays most wells (that were initially naturally flowing wells) are operated with submersible pumps.

It is noteworthy that the most favourable hydrogeological, hydrochemical and geothermal conditions are found in the southern part of Hungary around the cities of Szeged and Szentes, where a very dense thermal water well network exists (Figures 6 and 7).

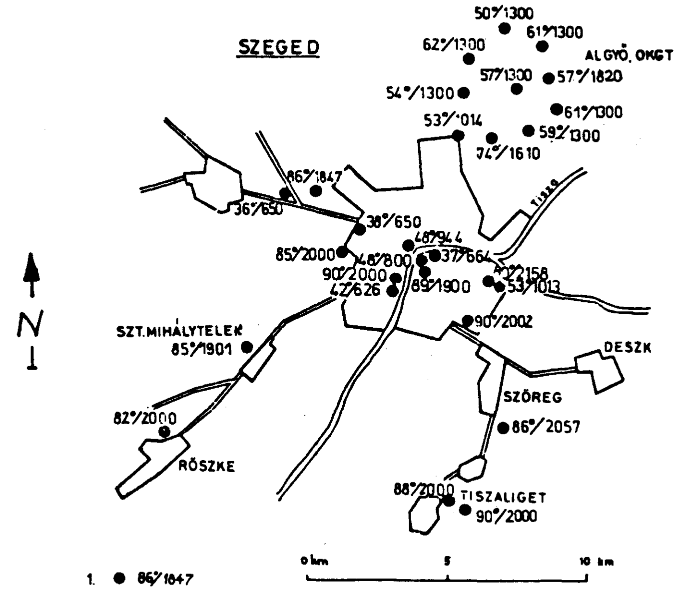

Figure 6: **Thermal water well field in Szeged (SE Hungary).**

Legend : 90° = well head (surface) temperature (°C); 2000 = thermal water yield in litres per minute.

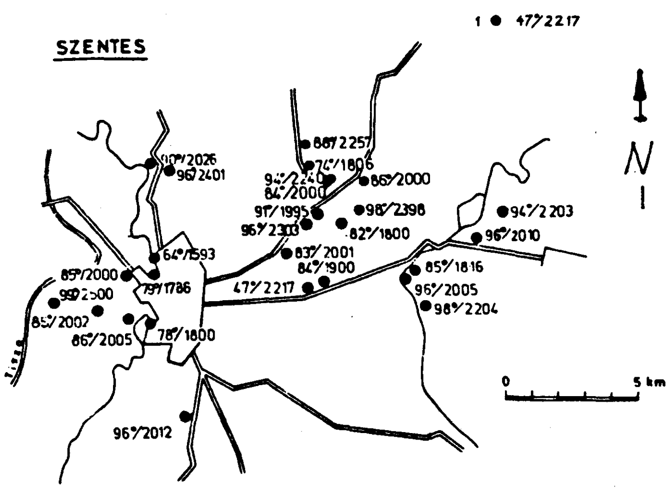

Figure 7: **Thermal water well field in Szentes (SE Hungary).**

Legend : 99° = well head (surface) temperature (°C); 2500 = thermal water yield in litres per minute.

Main types of the thermal water use

There is a wide range of thermal water use in Hungary. Thermal waters originating from Triassic carbonate aquifers are used almost completely for balneological and therapeutic purposes, but the Upper Pannonian thermal waters have a more diversified use. The main types of use for these low-enthalpy thermal waters are:

Non-energy use:

- Balneological and therapeutic use: Due to the abundance of thermal water resources and the great number of thermal wells, a highly developed balneological network and infrastructure was established in the whole country. Among the 1050 thermal water wells, a total of 280 wells are producing thermal water for all kinds of balneological and therapeutic purposes. There are 145 bathing resorts and spas in the country which are supplied by thermal water of different quality and temperature. Among them, about 70 well waters have been declared medicinal waters. The most famous bathing centres are Budapest, Héviz, Harkány, Hajduszoboszló, Debrecen, Gyula and Zalakaros. Some thermal waters are bottled and widely used as table waters or taken as medicinal waters in drinking cures.

- Drinking waters: In some parts of Hungary, because of special hydrogeologic and geothermal conditions, many water wells are yielding thermal waters of good quality which accord with drinking water standards. There is a total of 236 thermal water wells which supply drinking water.

- Domestic water supply: Thermal water for domestic water supply is used in the same environment where thermal wells are in service for district and space heating, mainly in south Hungary.

- Industrial use: An unusual use for thermal water is near Szeged, where it is used in an oil field for the purpose of secondary oil recovery. About 8000 m^3 of thermal water are withdrawn from 12 thermal water wells and repressured into the oil pools at the periphery of the oil field.

Energy source:

- District and space heating: There is a total of 14 thermal wells for district and space heating purposes in hospitals, apartments and schools. The most remarkable district heating project was realized in Szeged where about 1000 flats are supplied by thermal water at 89°C.

- Agricultural use of geothermal energy: This is a very important branch of thermal water use. A total of 258 thermal water wells supplies geothermal energy for this purpose. Greenhouses covering about 500 000 m^2, and plastic tents, tunnels and soil heating facilities covering about 1,2 million m^2 are supplied with thermal water at 60 to 95°C. About 80 percent of all existing greenhouses-glasshouses in the southern part of Hungary

HYDROGEOTHERMAL RESOURCES IN THE EUROPEAN PART OF THE FORMER U.S.S.R.

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ABSTRACT

This contribution deals with the description of geological structural and geothermic features in the European part of the former USSR. The knowledge of hydrogeothermal resources and methods of their estimation are presented. Basic hydrogeothermal systems are described and their potential for thermal water extraction are assessed.

SPECIFIC FEATURES OF THE GEOLOGICAL STRUCTURE IN THE EUROPEAN PART OF THE FORMER USSR

The study area has many different geological and tectonic features and structures which vary in age and origin (Figure 1).

The major part of the territory lies within the ancient Precambrian East European platform which is fringed by the Scythian and Turan Epipaleozoic platforms in the south and southeast, the Fore-Karpaty trough in the west, and the Fore-Urals trough in the east.

Since the Riphean period the East Russian platform has undergone downwarping which resulted in the formation of a rather complex structure with large synclinal troughs (the Baltic, Moscow, Caspian, etc.), anticlinal uplifts in the ancient shields (the Baltic, Ukrainian) and major anticlinal structures (Belorussian, Voronezh).

The geology can be interpreted as two structural stages: (a) a lower stage represented by a crystalline basement composed of metamorphic and magmatic Archean and Lower - Mid Proterozoic rocks, and (b) an upper stage comprising a platform cover of undisturbed and slightly altered sedimentary layers of systems ranging from the Upper Proterozoic to the Quaternary.

The Scythian plate separates the East European platform from alpine folded structures of the Crimea and Caucasus. The plate, as well as the Fore-Dobruzhinsk-, Inzol - Kuban and Terek - Caspian marginal troughs, which confine it in the south, stretches from the west to the east.

The Pre-Jurassic plate basement has a complex structure, comprising a number of large depressions and uplifts with fractured flexures. Sedimentary cover of the plate is represented by a Mesozoic - Cainozoic rock mass with a thickness of 3-10 km. The Karpaty - Crimean - Caucasian alpine folded area and the adjacent intermontane depressions and troughs (Transcaucasian, Rioni and Kura) are composed mainly of sedimentary and volcanogenic sedimentary Cainozoic and Mesozoic rocks.

BRIEF DESCRIPTION OF A GEOTHERMAL FIELD: ARCHEAN AND PROTEROZOIC TECTONIC STRUCTURES

The entire Russian plate is formed by Archean and Proterozoic tectonic structures. The heat flow is relatively constant (Figure l). Regional weak heat flows in the range 25 to 40 mW/m^2 correspond to the main upper crust blocks composed of basic and ultrabasic rocks. Regional values of between 40 and 60 mW/m^2 occur mainly in the upper crust blocks which contain intermediate and acidic rocks.

Regional variations of heat flow are thus attributed to differences in the heat generated in the crust. Major reasons for local variations are groundwater circulation and the heat flow refraction due to complicated geological conditions (e.g. salt domes).

Paleozoic tectonic structures

The heat flow value of the Epipaleozoic platforms varies around 60 mW/m^2. Anomalies are oriented along the general length of these structures. Higher heat flow values are typical for the young structures. A similar situation is observed in the Pechora depression that was reactivated during Devonian and Permian periods, as well as in the Dnepr - Donetsk basin and the Pripyat depression (Figure 1).

The heat flows in the Paleozoic structures of the Urals are low, ranging from 20-40 mW/m^2. This is the largest Asian "cold area" and it extends southwards into the Urals depression.

Cainozoic tectonic structures

Four basic zones of heat flow can be recognized and linked to the classification of the principal heterogenic tectonic structures: (1) high heat flow of 70 to 110 mW/m^2 within eugeosynclinal zones; (2) medium heat flow of 50 to 70 mW/m^2 in monogeosynclinal zones of the global compression belts (the Karpaty, Crimea, Big Caucasus and Alpine Himalayas belt as a whole); (3) low heat flow in intermontane and epicontinental marine depressions (Black Sea, the Rioni, Kura and South Caspian depressions). Corrections for the nature of the sedimentary column imply that the values of the background heat flow are 1,5 to 2,5 times greater than the measured ones; (4) low heat flows are found within the alpine depressions, though the values observed are close

Figure 2(A)

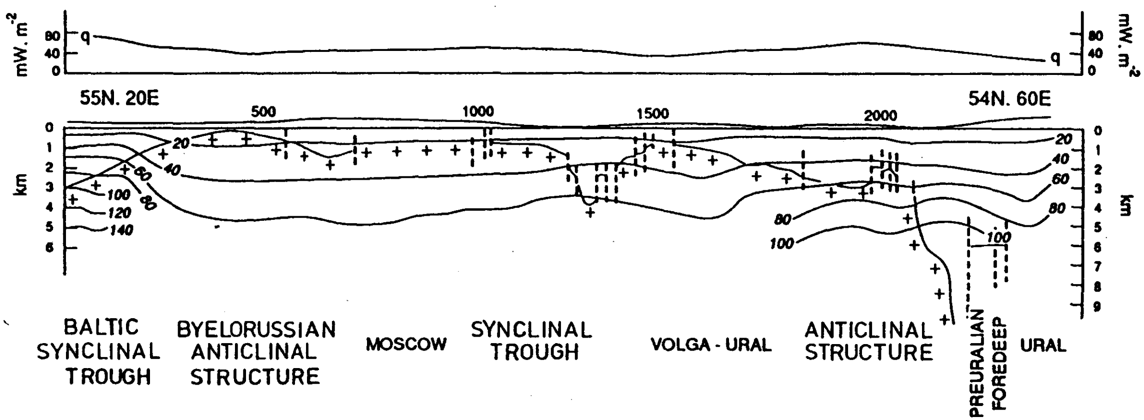

Figure 2: Geological and geothermal profiles through the main tectonic units of the European part of the former USSR: **2A** - Baltic Sea - Urals (I); **2B** - Polar Urals - Caucasus (II); **2C** - Carpathians - Turanian Plate (III: foredeep - FD; Folded Carpathians - FC; Trans - Carpathian depression - TC).

A pioneer work was the country's first *Thermal water map of the USSR* (1968) which showed the basic distribution of thermal water, the occurrence of thermal waters in tectonic structures, the extent of knowledge and the potential of various areas in terms of thermal water reservoirs, as well as giving procedures for prospecting, exploring and evaluating thermal water storage. This work contributed greatly to the solution of the problems associated with geothermal studies. By the early 1970s, a number of generalized monographs on thermal water resources (Goldberg & Yazvin, 1966; Frolov & Yazvin, 1969), had been published. They contained descriptions of prospective areas and regions established using a set of geological-structural, geothermal and hydrogeological parameters, as well as assessments of thermal water storage for those territories having heat and power potentials equal to 30-40 million tonnes of conventional fuel per year.

The next stage involved developing the theory, methodology and technical-economic criteria for hydrogeothermal production, as well as protection of the environment against thermal and chemical pollution.

All these aspects were considered when reassessing thermal water resources in the country (Kulikov & Mavritsky, 1984; Mavritsky, Shpak, *et al.*, 1983) and in some prospective regions (Shpak, Orfanidi, *et al.*, 1985). New methodologies were defined and norms to be adopted for geological exploration, estimation of the available resources and their approval by the former USSR Commission on Mineral Resources (Sekei & Shpak, 1986; Shpak, 1980).

As a result, it has become obvious that hydro-geothermal development based on the recirculation of the thermal water after use, by injection into the producing aquifer, is viable in geological-economic and environmental terms. Though it is very expensive and energy consuming, it allows a considerable increase in the scale of production and utilization of hydrogeothermal resources. Today this view is accepted in the former USSR in planning studies for thermal water development and commercial use. The various stages in the production process are as follows. The organization responsible for development and production of geothermal fields, extraction and sale of the natural heat to the consumers is the former USSR Ministry of Gas Industry, which is also in charge of geological exploration in some regions. Thermal water prospecting and exploration are generally carried out by the former USSR Ministry of Geology. After the availability of the resources has been confirmed, development of the geothermal reservoirs becomes the responsibility of the former USSR Ministry of Gas Industry.

TYPES OF HYDROGEOTHERMAL RESOURCES

Two types of geothermal resources are distinguished in the former USSR: hydrogeothermal and hot dry rock (Mavritsky & Shpak, 1983; Shpak, 1975). Hydrogeothermal resources are geothermal resources of natural aquifers in which the heat is transported by groundwater, steam and water-steam mixtures. Hot dry rock resources are related to the heat stored in virtually impermeable rocks. Development and economic use of hot dry rock resources require the solution of some complicated scientific and technological problems concerned with creating artificial circulation systems and sub-surface heat systems which will be efficient in terms of hydrodynamics and thermophysics. Such systems have been studied theoretically and a number of experimental studies have been carried out both in the former USSR and abroad. However, as yet, it is still too early to speak about commercial technologies that would enable the creation of such subsurface systems under various geological conditions.

Economic use of geothermal resources thus currently depends on the resources distributed by natural heat carriers, i.e. the hydrogeothermal resources. The distribution and potential of these resources in the former USSR is given in Table 1 (Sekei & Shpak, 1986; Shpak, 1980). The table shows the succession of study and categorization of the available hydrogeothermal resources adopted in the former USSR.

The availability of hydrogeothermal resources, or the safe yield, is the amount of heat and water which can be extracted from the aquifer or aquifer system under investigation bearing in mind the available technology and the economics, according to the production rate and the quality of the heat carrier (i.e. temperature, chemical and gaseous composition), for a given period of production. The available heat resources are assessed either in terms of power, or as tonnes of conventional fuel (t.c.f.) per year (1 t.c.f. = 29,2 GJ), and the safe yield is measured in terms of volumetric water discharge (l/sec, m^3/day) or bulk discharge (kg/sec, t/day) for steam and water-steam mixtures.

The terms "safe yield" and "available resources" are synonymous. However, the "safe yield" is usually used to assess the potential use of thermal water for satisfying the needs of particular demands for heat power, subject to approval of the resource use in accordance with the regulations. But when potential production of thermal water is estimated for a region, as a rule by means of regional assessments, the term "available resources" is to be preferred.

The experience available from the use of thermal water in heat and power engineering enables classification of the resources by qualitative parameters.

It seems reasonable to assume 20°C as the lowest temperature for thermal water in the context of potential applications using heat pumps and the demand in many industries for subthermal (low-thermal, semi-thermal, or even thermal - according to various authors) heat carriers within the temperature range of 20-40°C.

The following classes of thermal water can be defined by the potential water use for heat and power supply:

- Low temperature water (20-100°C), which includes a subdivision of water with a temperature of 20-40°C which can be used in heat engineering by means of heat pumps. Moreover, it can be effectively used to thaw frozen ground and exploit placers, promote fisheries, heat the soil for agriculture, as well as for injection into oil reservoirs; all technological processes which require low temperature heat carriers. Low potential water is mainly used for supplying heat to industrial, agricultural and municipal organizations.

  The efficiency of such low temperature water in heat engineering can be increased by installing special heating and ventilation systems that are designed for the use of low and medium heat carriers including a combined application of these systems and heat pumps.

Depending on the complexity of the geological, hydrogeological and geothermal conditions which affect the exploration process and the safe yield assessment, all thermal groundwater reservoirs or parts of large reservoirs (i.e. units of independent commercial development) are subdivided into three general groups.

- *Group-I*: Reservoirs with simple hydrogeological, hydrochemical and geothermal conditions. The thermal water occurs in undisturbed aquifers of uniform thickness and structure, with relatively uniform hydraulic conductivities and gradual, regular changes in hydrogeochemical properties and temperatures. Confined resources are the main sources of the available resource formation. Other sources can also be established and quantified using the exploration data or the experience available in developing similar reservoirs. Combination of natural environments typical of the group-I reservoirs determines the potentials for economically sound exploration of A-category resources.

- *Group-II*: Reservoirs with complicated hydrogeological and geothermal conditions as a result of varying thicknesses and structure of the aquifers and non-uniform hydraulic conductivities of water-bearing rocks, or with complicated hydrochemical and geothermal conditions.

  The safe yield of reservoirs (or parts of reservoirs) of this group is formed at the expense of mainly confined resources. Other formation sources are subjugated and can be rather reliably quantified using exploratory data or the data of regime observations.

  Due to the high cost of geological exploration, the available resources of this group are generally explored according to B-category criteria and only partly A-category.

- *Group-III*: Reservoirs (areas) with extremely complicated hydrogeological conditions as a result of the highly variable thicknesses and structure of the aquifers, the variable hydraulic conductivities of water-bearing rocks, the limited (local) distribution of aquifers and reservoirs, and the rather complicated hydrochemical and geothermal conditions.

  Groundwater reservoirs of this type usually occur in irregularly developed tectonic fractures which extend through intrusive metamorphic, volcanogenic-sedimentary and carbonate rocks (including karst systems), as well as aquifer systems with complex structures and many faults. The hydrogeological role of the faults varies and must be quantitatively defined during exploration. Hydrogeochemical and temperature conditions are not uniform and the boundaries are complicated.

  Production can be associated with water inflows from the adjacent aquifers and fissured zones. The sources of the resources are often hard to establish and quantify even after exploration.

  To establish A-category resources after detailed exploration seems inappropriate for the Group-III reservoirs (or areas), because of the high cost and low effectiveness of geological exploration. The available resources of such reservoirs are thus investigated mainly according to B-category criteria and partly to C_1-category.

The following percentages of explored reservoirs (or areas) with approved economic thermal water resources are considered as prepared for commercial development in the USSR:

Resource category	Reservoir complexity or area complexity group		
	I	II	III
A + B	80	80	70
including A not less than	40	20	--
C_1	20	20	30

Other conditions necessary for a reservoir (or area) to be prepared for commercial development are as follows:

(a) The quality of thermal water (heat carrier) must be studied in detail and involve all parameters in accordance with the requirements for its future use. Proof must be given that its composition is constant or varies within tolerable limits during an estimated period of production.

(b) Technological characteristics of the heat carrier must be studied in detail to provide the initial data sufficient to design a technical scheme of use that incorporates the utilization of all possible applications (heat and power generation, extraction of commercial constituents, application to balneology and recreation, etc.).

(c) Thermal water production must be studied in detail to obtain the initial data for use in designing a project for the development of a reservoir (area).

METHODS FOR ESTIMATING THE SAFE YIELD OF THERMAL WATERS

The estimation of the safe yield of thermal waters consists of determining the possible productive capacity for a given or predicted decline of water levels in wells.

At the same time, it is necessary to prove that during abstraction of the thermal water its quality (temperature and chemical composition) will correspond to requirements during the whole period of exploitation.

The safe yield is estimated for development areas and exploitation sites with the aim of proving the design of water intakes for supplying defined objects with heat power raw materials and also for proving general schemes for water use in the national economy of large hydrogeological regions, as well as trends and volumes of prospecting and exploration work.

Both hydrodynamic and hydraulic methods of groundwater safe yield estimation have certain disadvantages. For hydrodynamic methods (especially when using analytical solutions) it is necessary to strictly schematise the natural situation and to define hydrogeological parameters. The hydraulic method, based on a defined empirical relation, does not pose such requirements but the duration of operational pumping, in order to determine empirical relations, is incommensurately small when compared to a calculated period of well pumping for production. This is especially true for deep thermal waters that are being developed under intransient fluid filtration.

Combined use of hydrodynamic and hydraulic methods can be very effective. In these cases water level lowering is determined by hydraulic method under projected well yields (considering their interaction) for the period of test pumping. Additional water level lowering $\Delta S(t)$ at the end of the calculating period under the same well yield is determined by the hydrodynamic method.

Regional estimation of thermal water safe yield is aimed at establishing the importance of heat power resource compared to fuel and power for different economic regions and the country as a whole. Results of this estimation should serve as a basis for working out general schemes of heat exploitation, providing for volumes and the rational sequence of prospecting and exploration work. The volume of safe yield is determined not only by a complex of natural (geological, structural, hydrogeological and geothermic) conditions, but also by a number of technical and economic restrictions and characteristics (schemes and regimes of water well exploitation, their number, distance between them, technology of withdrawal, etc.). At the stage of regional estimation the main problems of environmental protection are considered from the point of view of thermal and chemical pollution and also of rational use according to depth.

The technique of regional estimation worked out in the former USSR is based on geological and economic principles oriented to the use of computers, provides the most rational solutions to the problems mentioned and also considers the characteristics and special features of thermal water as a heat carrier (Shpak, 1980; Sekei & Shpak, 1986).

BASIC HYDROGEOTHERMAL SYSTEMS

Brief descriptions of the hydrogeothermal systems of the East European part of the former USSR

East Europe is characterized by a great variety of geothermal, geological, structural and hydrogeological conditions that define different prospects for particular regions in terms of geothermal energy potential (Figures 3 and 9).

There are several hydrogeothermal regions within the area: the East European (Russian) and Scythian platforms, as well as the Carpathian - Crimean - Caucasus and the Urals fold belts. Two types of confined water systems can be distinguished: strata and fissure systems.

The confined sedimentary water systems, which occur in platform areas, intermontane depressions and marginal troughs, are characterized by a gradual increase in temperature, mineralization and

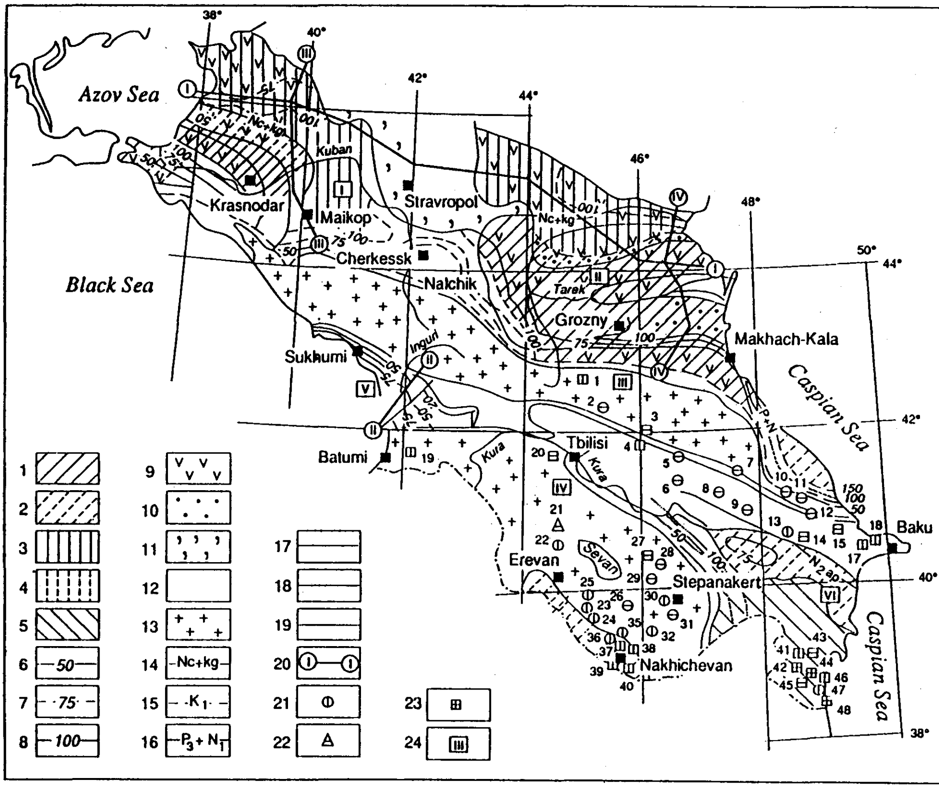

Figure 3: **Map of potential regions of the South European part of the former USSR for geothermal energy recovery - scale 1:2 500 000 (Editor: A.A. Shpak; Compilers: G.K. Antonenko, B.F. Mavritsky, A.A. Shpak, B.I. Kononov & Ya.B. Smirnov).**

Legend: **1** - regions where "upper" thermal aquifer is of particular interest in terms of exploitation; **2** - regions where "upper" thermal aquifer is of second-order interest in terms of exploitation; **3** - regions where "medium" thermal aquifer is of particular interest in terms of exploitation; **4** - regions where "medium" thermal aquifer is of second-order interest in terms of exploitation; **5** - regions where "lower" thermal aquifer is of particular interest in terms of exploitation; **6** - isotherms of "upper" thermal aquifer; **7** - isotherms of "medium" thermal aquifer; **8** - isotherms of "lower" thermal aquifer; **9** - potential regions for extraction of low-entalpy geothermal energy (t < 150°C); **10** - potential regions for extraction of high-entalpy geothermal energy (t ≥ 150°C); **11** - potential regions for extraction of ultra low-entalpy geothermal energy; **12** - regions where no thermal aquifers occur; **13** - folded areas; **14** - boundary of "upper" thermal aquifer; **15** - boundary of "medium" thermal aquifer; **16** - boundary of "lower" thermal aquifer; **17** - boundary between regions with different potentials for exploitation of geothermal energy; **18** - boundary of geological - structural areas; **19** - fractures; **20** - section line; **21, 22, 23** - sources, hatching inside symbols - temperature: vertical lines up to 30°C, horizontal lines - 30-50°C, cross hatched - 50°C; **24** - names of artesian basins: I - Azov - Kuban, II - Tersk - Kumsk, V - Rioni, VI - Kuril and Kusero - Divichinsk; names of folded areas: III - Bolshoi Caucasus, IV - Maly Caucasus.

water pressure of the thermal water with depth, as well as by fairly regular changes in the chemical and gas composition of the water and the hydraulic conductivity of the rocks, both with depth and areally.

According to the hydrogeothermal conditions, sedimentary confined water systems within the region are subdivided into two types:

(1) confined water systems of the Pre-Cambrian East European platform and the related piedmont troughs, composed of Paleozoic rocks. Maximum temperatures of the thermal water in the systems amounts to 50-75°C and rarely 100°C;

(2) confined water systems of the Scythian Epi-Paleozoic platform and adjacent piedmont troughs, as well as intermontane depressions composed of Mesozoic-Cainozoic rocks. Temperatures of thermal water reach 100-200°C and sometimes exceed this.

Unlike sedimentary confined water systems, in fissure complexes associated with folded areas the thermal water circulates in complicated fissure systems. Usually it is rather difficult to determine the areas of recharge and flow directions, but discharge sites are located at intersections of tectonic faults where erosion has produced thermal springs.

Within the study territory confined water systems of the fissure type can be subdivided into:

(1) areas and regions of Cainozoic (Alpine) folding composed mainly of sedimentary and volcanogenic-sedimentary rocks of Cainozoic and Mesozoic age (the Carpathians, the Crimea and the Caucasus);

(2) areas and regions of Hercynic (the Urals) and Baikal (Timanian uplift) folding.

The most promising regions for the extraction of thermal water, in terms of their hydrogeological and geothermal conditions, are the confined water system of the Scythean Epi-Paleozoic platform, as well as intermontane depressions (Rion, Trans-Carpathian, etc.) of folded mountain regions of Alpine age.

Hydrogeothermal systems of the Pre-Caucasus and Crimea

There are two large prospective regions in the Scythean artesian area: the Pre-Caucasus and the Crimean Plain.

The Pre-Caucasus: Hydrogeologically, this area is a multi-layer confined water system comprising a series of inter-connected artesian basins: the Azov-Kuban, Tersk-Kum, Tersk-Suzhensk and the hydrogeological area of the Stavropol arched uplift (Figures 4, 5, 6 and 7). Thermal water is associated with Mesozoic - Cainozoic sediments, among which the most favourable for practical utilization are the Chokrackaragan and Lower Cretaceous aquifer complexes shown on the map.

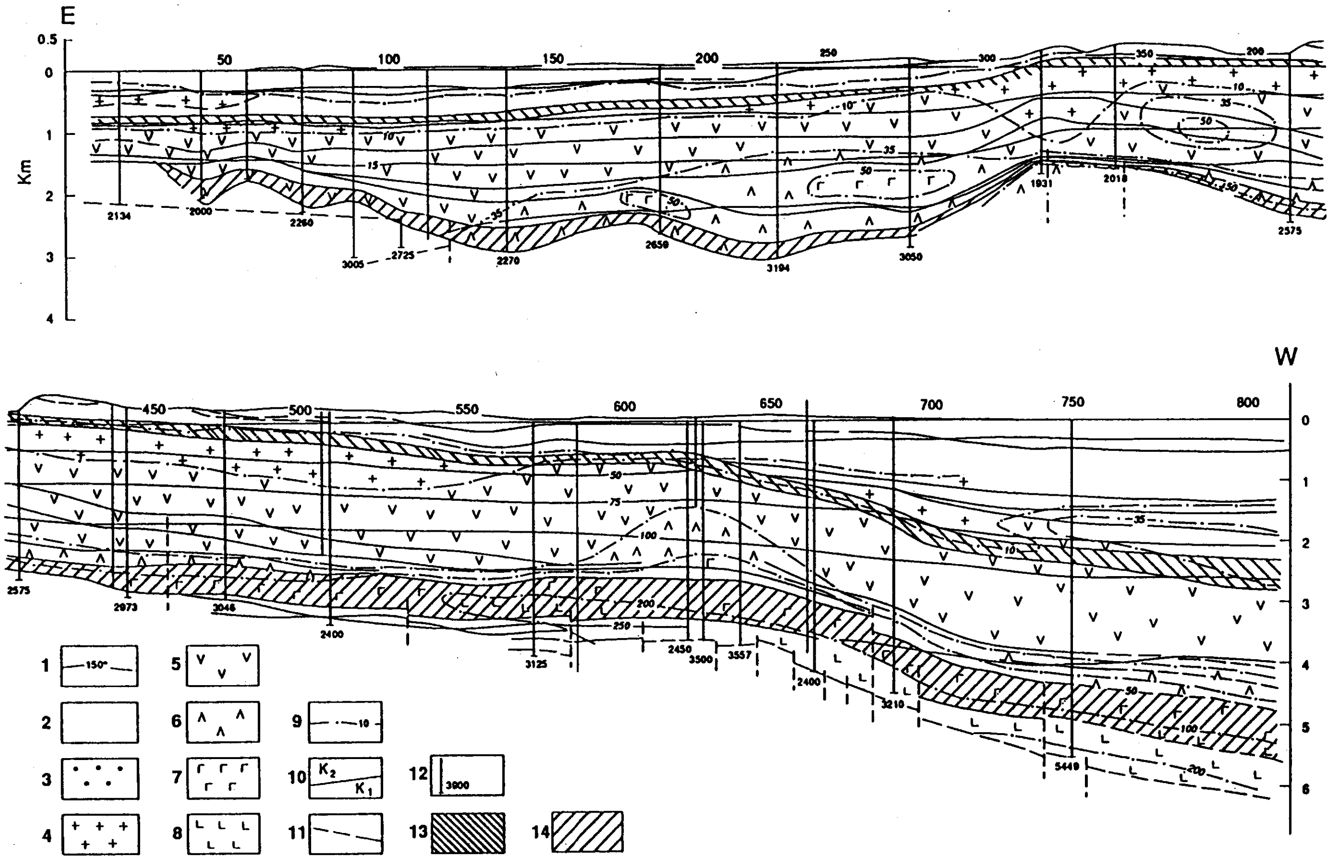

Figure 4: Hydrothermal cross-section along line 1-1.

Legend (and also for Figures 5-7): **1** - **isotherms; 2-8** - **mineralization (g/l): 2** - **up to 1 g/l; 3** - **1-3; 4** - **3-10; 5** - **10-35; 6** - **35-50; 7** - **50-100; 8** - **> 100; 9** - **boundary of zones with different mineralization; 10** - **stratigraphic boundary; 11** - **tectonic disturbances; 12** - **borehole: above - name, below - depth; 13, 14** - **prospective water-bearing complexes for thermal water recovery.**

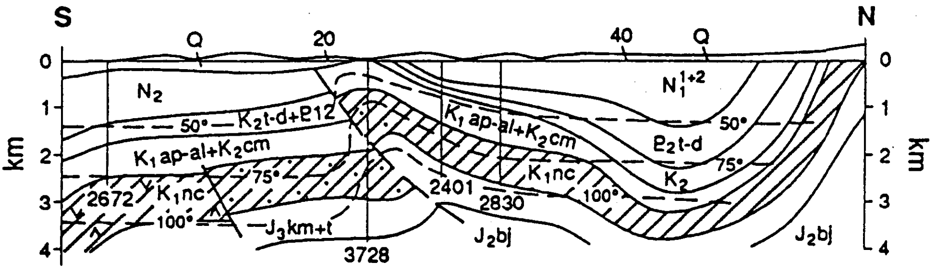

Figure 5: Hydrothermal section along line II-II.

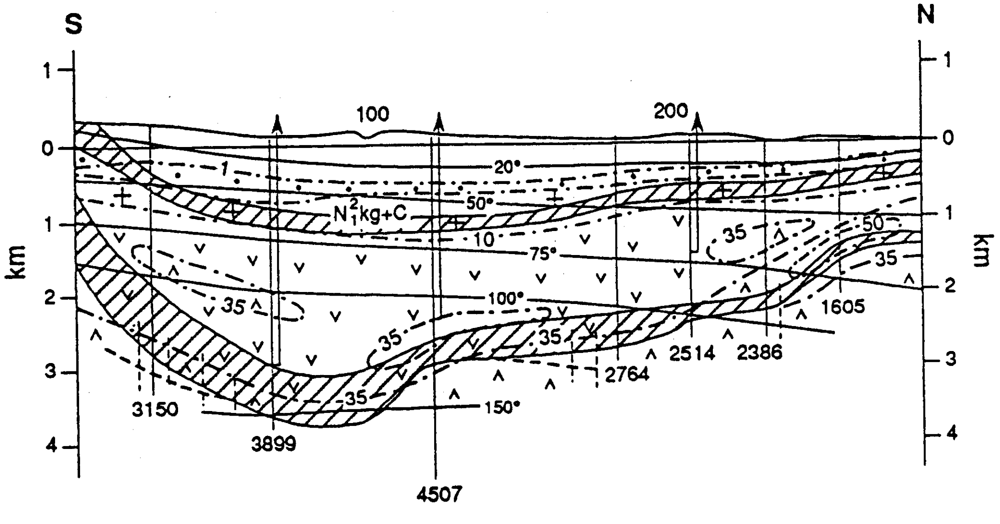

Figure 6: Hydrothermal section along line III-III.

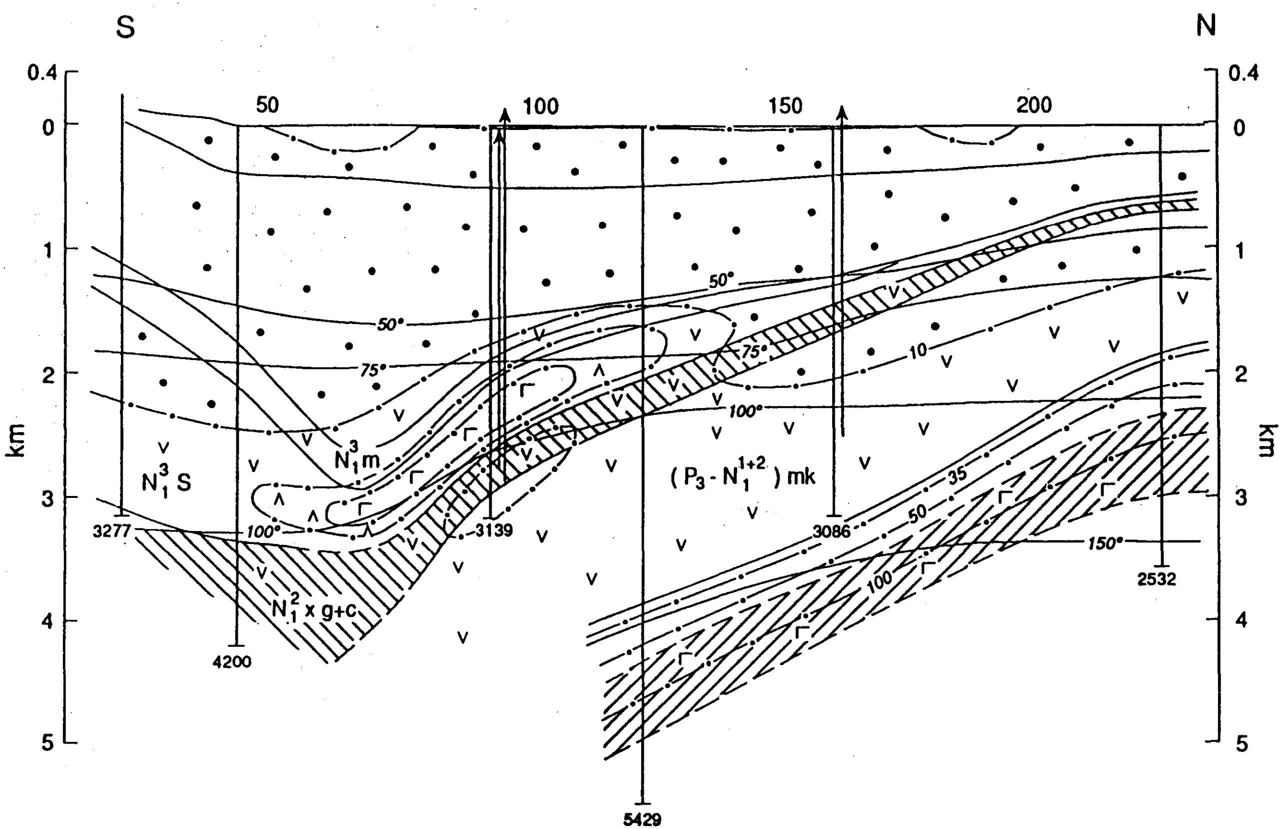

Figure 7: Hydrothermal section along line IV-IV.

The Chokrakaragan aquifer complex is spread over almost all the Pre-Caucasian area and is contained in the marine terrigenous and partly carbonaceous formations. The total thickness of the deposits varies from 20-50 to 900 m or more. Maximum depth is 2800-3600 m. The water ranges from fresh to brine with mineralization of 0,5-65 g/l. Chemically, it is nitrogen-methane sodium bicarbonate water. The groundwater temperature in the Chokrakaragan complex varies with depth from 10 to 150°C. The water of the complex is tapped by wells and the temperature at well head ranges from 50 to 70°C (Makhach - Kala) and up to in excess of 100°C (Kizlyar, Khankala). The transmissivity reaches 100-200 m^2/d in the east of the Pre-Caucasus, decreasing in the west to 20-50 m^2/d. The highest values are observed in Grozny and Makhach - Kala regions where they are 150-300 m^2/d.

The largest thermal area in the Chokrakaragan aquifer system is the Hankal reservoir. This is located in the Grozny region within the Tersk-Sunzhensk artesian basin. Structurally the reservoir represents a periclinal uplift with a gently sloping, narrow arch and steep flanks (Figure 6). The central part of the uplift is associated with an oil field that is being developed. The sequence contains about 24 sandy beds interbedded with clays. Those of commercial importance for thermal water extraction are the thickest, highly permeable and extensive layers (IV-VII, XIII, XVI and XXII). The Hankal area has a very variable geothermal anomaly due to intensive convective heat fluxes from below. Productive layers of the arch centre, at a depth of 600-1200 m, thus have temperatures of 95-105°C and geothermal gradients of 10^{-1} °C/m. In the flanks of the pericline the depth of the productive layers sharply increases to 2000-2500 m and geothermal gradients drop to $(4\text{-}4{,}5) \times 10^{-2}$ °C/m. Water heads are high and are 35 to 130 m above the ground surface and flowing well yields are 1500-3500 m^3/d. The water is mainly fresh (0,9-2,1 g/l), of sodium bicarbonate type. It is not corrosive and does not tend to precipitate salt in wells, or in water- and heat equipment. In 1968 the thermal water capacity, under flowing conditions and ignoring the fact that water extraction influences the natural regime of thermo-mineral springs used in balneology, amounted to 9700 m^3/d for seasonal use (greenhouse complex, fruit canning factory). To meet the increased heat needs caused by expansion of the greenhouses and to supply municipal hot water, a circulation system was introduced in 1982 to inject the used thermal water into reservoir layer XIII (Figure 8). This has increased the water yield and restored hydrostatic pressures. The same circulation system is now under development for layers IV-VII, XVI and XXII, providing the potential for a partial heat supply for Grozny.

The Lower Cretaceous water-bearing complex is also spread over almost all the Pre-Caucasian area. The depth is over 2000 m. Maximum depths of wells in the foredeeps are 4000-5500 m. The lithology comprises conglomerates, clays, sandstones and siltstones. Over most of the area saline waters or brines (with mineralization of 10-150 g/l) are predominant and it is only in the marginal parts (Adygei trough) that fresh and brackish waters occur. Temperatures of the Neocomian water-bearing sedimentary complex vary from 10 to 170°C. In the major deep wells water temperatures exceed 100°C. The water is confined, well yields are 100-5000 m^3/d, and the transmissivity varies from 10 to 50 m^2/d, increasing to 100-150 m^2/d in the East Kuban basin.

The reservoirs with the greatest domestic value are associated with the Lower Cretaceous water-bearing complex in the Mosty, Ulianovsk, Voznesenskoe and Labinsk areas, etc., which are in the southeastern marginal part of the Azov-Kuban basin. Their favourable geological-economic parameters, i.e. the extensive occurrence of low-mineralized (1,2-3 g/l) water and high

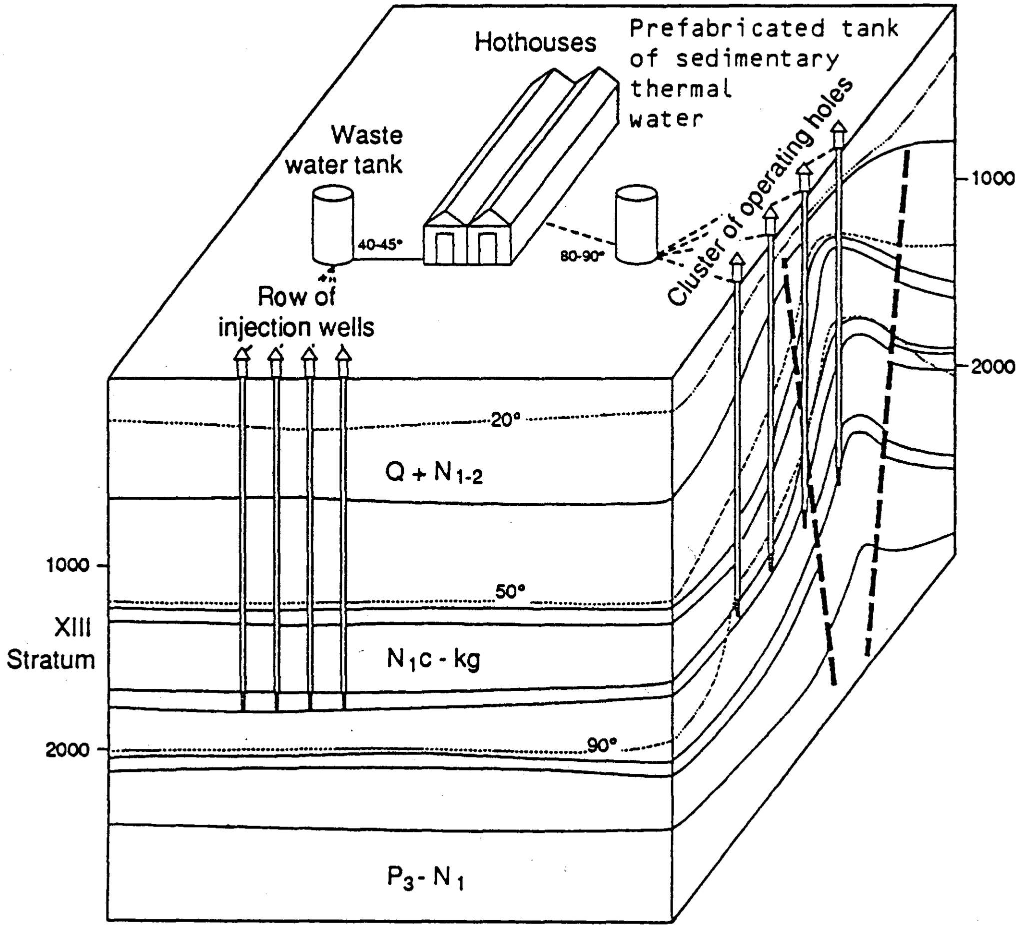

Figure 8: Block diagram of Hankal reservoir.

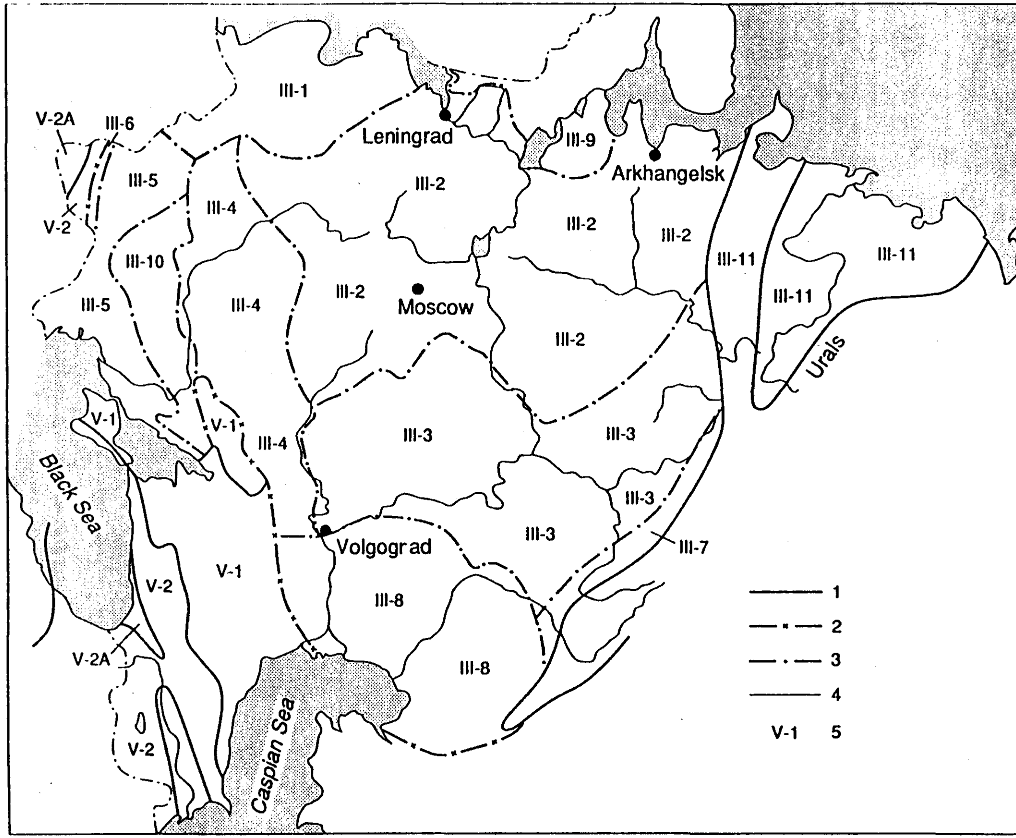

Figure 9: **Chart of hydrogeological zoning in the East European part of the former USSR.**

Basins: III-1 - Baltic - Polish; **III-2** - Middle Russian; **III-3** - East Russian; **III-4** - Dnepr - Donetsk; **III-5** - Volyn - Black Sea; **III-6** - Fore-Carpathian; **III-7** - Fore-Urals; **III-8** - Caspian; **III-9** - Baltic Sea; **III-10** - Ukrainian; **III-11** - Timan - Pechora.
V-1 - Scyphian area; **V-2** - Carpathian - Crimean - Caucasus area; **V-2A** - Intermontane basins.

permeability are attributed to the existence of a rather broad tectonically weak zone extending in an anti-Caucasus direction. The geological cross-section of the region shows 3-4 productive sandy layers with a thickness of 65 to 120 m at a depth of 1500-2900 m. Temperatures increase with depth from 70 to 120°C. Water pressures above the ground surface vary from 25 to 75 m. Yields of flowing wells amount to 2000-3000 m^3/d. Due to their close proximity, all the areas interact with each other during exploitation. Because of this, the thermal water resources were assessed using a mathematical model. This showed that these resources, under a natural flowing regime, do not exceed 15000 m^3/d (for a 25 year exploitation period), but when developed with submersible pumps they are much greater. However, the problem that has to be solved is that concerning disposal of the thermal water after use, as it contains many dangerous components. In this context, a project is being implemented that provides for the reinjection of waste water into the producing reservoir after use. This will enable an increase in water extraction to 80000 m^3/d at a temperature of 80-100°C and, at the same time, protect the environment against thermal and chemical pollution. The water is used in agriculture (e.g. for heating greenhouses, cattle breeding complexes, fisheries) and for municipal and technological requirements.

In addition to the Pre-Caucasian thermal areas just referred to similar applications, including balneology, are applied to thermal water reservoirs of Makhach-Kala, Ternair, Kizlyar, Cherlensk and Cherkask, amongst others.

The Crimea Plain: The Crimean Plain is part of the western area of the Scythian platform. Potential thermal water reservoirs are the Lower Cretaceous (Neocomian - Aptian) and Danian - Paleocene water-bearing complexes. Neocomian - Aptian thermal waters are associated with fissured limestones and conglomerates. They occur at depths varying from several metres in the Simferopol uplift to more than 2400 m in the north of the Crimea. The water is confined, and the average yield of flowing wells is 1000 m^3/d. The transmissivity varies from 20 to 100 m^2/d. The temperature at the well head is 25-70°C, while rock temperatures range from 40 to 180°C. Water mineralization is between 1 and 78 g/l, and with increasing mineralization the water type changes from sodium bicarbonate and sulphate to sodium-calcium-chloride, and the gas composition from nitrogen to methane. Danian-Paleocene water is associated with fissured limestones and marls. The thickness of the water-bearing rocks varies from 30-40 to 60-70 m. Well piezometric levels are 20-50 m above the ground surface. The transmissivity varies from 20 to 80 m^2/d, and the rock temperature is 40-120°C. Chemically the water is a sodium bicarbonate to sodium-calcium-chloride type. Mineralization ranges from 1 g/l in the east of the Crimea to 20-25 g/l in the Tarkhankutsk Peninsula. Currently the area is being intensively explored and practical use of thermal water has already started.

Trans-Carpathian hydrogeothermal system

The Trans-Carpathian basin is associated with the trough of the same name, which is located between the Carpathian folded area and the Hungarian middle sedimentary basin and separated from them by deep faults. The basin is composed of a thick (up to 2000 m) molassic deposit of Neogene sediments with salt-bearing layers overlying a complex folded basement. The highest temperatures were observed in the Chop - Mukachevo depression (in Zaluzh region the temperature is 146°C at a depth of 2620 m, in Mukachevo - 157°C at a depth of 3,343 m). Major thermal water complexes are the Helvetian - Tortorian and Sarmatian - Levantinian volcanogenic-sedimentary rocks that are characterized by high temperatures (40-150°C).

Trans-Caucasian hydrogeothermal systems

The Rioni basin is located between the southern slopes of the Major Caucasus and the northern slopes of the Adzhar - Trialet ridge. The eastern boundary of the basin is the Dzirulsk massif; in the west the sediments of the basin are below the level of the Black Sea. The total area of the basin is 8000 km^2. The Neocomian carbonate water-bearing complex has the greatest potential for thermal water use. The high productivity of the complex is due to its great thickness (the total thickness varies from 400 to 1760 m), high flow of water through fissures (the transmissivity averages 100 m^2/d), and favourable conditions for recharge (Figure 5). Well yields vary from 500 to 8500 m^3/d. Over a large part of the basin the water of the Neocomian complex is fresh or brackish with a temperature of 80-105°C at well heads. In the Rioni basin a number of thermal water fields have been explored (Zugdidi, Tsaishi, Okhurey, Kindga - Mokvinsk, etc.) and the water is used for heating greenhouses, municipal and domestic needs, balneology and other purposes.

The Kurinian Kusar - Divichinsk basins are located between the Major and Minor Caucasus and dip below the Caspian Sea. Potential water-bearing complexes within the basins are the complexes of the Apsheron deposits, the productive rock mass and the Maikop series (the latter only within the Kurinian depression). The water temperature of the Apsheron water-bearing complex does not exceed 80°C, whereas in other complexes it is higher than 100-120°C at a depth of 4000 m (Kurinian depression). Among these three complexes that of the Maikop has the greatest potential for utilization. The basins are now being explored.

The East European platform artesian area

A major part of the European region of the former USSR is formed by the artesian area of the ancient East European platform, which is composed mainly of Paleozoic rocks containing widespread brines. The platform is characterized by a moderate heat regime which determines that thermal water-bearing systems lie at depth. Within the region there are a series of large artesian basins which are interconnected to varying extent (Pechorsk, Moscow, Dneprovsk - Donetsk, Caspian, etc.). In these basins the main thermal water-bearing systems are developed, as shown on the map. Over the major part of this artesian area the basic water-bearing system is Devonian in age and composed of terrigenous carbonate rocks. The water is a sodium-calcium chloride type with a mineralization of 100-300 g/l and temperatures of up to 60°C at a depth of 2500-3000 m. Thermal brines also occur in Permian water-bearing complexes in the Pechorsk, Caspian, Dneprovsk - Donetsk and Pre-Urals basins.

Saline and brine thermal waters with a temperature of over 40°C occur in Mesozoic sediments of the Baltic - Polish and Caspian artesian basins. Due to the low hydraulic conductivity of rocks the well yields do not exceed 80-200 m^3/d; water temperatures at well heads are usually less than 40°C, though at a depth of 2500-3000 m they may sometimes reach 75-85°C.

At present these waters have little potential for supplying heat. The water with a temperature of 10-40°C may be of some value if used with heat pumps. Waters with a temperature of 10°C

Table 2: Potential thermal water resources and their heat power in sedimentary confined water systems in the European part of the former USSR.

Artesian areas and basins	Water-bearing complexes	Temperature (°C)	Mineralization (g/l)	Methods of production : Without maintenance of hydrostatic pressures: Flowing (m^3/d) $\times 10^3$	(Gcal/y) $\times 10^3$	Pumping (m^3/d) $\times 10^3$	(Gcal/y) $\times 10^3$	With maintenance of hydrostatic pressures: (m^3/d) $\times 10^6$	(Gcal/y) $\times 10^6$
Scythian platform artesian area	Chokrackaragan	45-140	1-100	80	2020	513	11731	125,3	2147
	including	>50	<10	65	1567	390	8599	115,6	2188
	Lower	60-150	1-120	150	3425	1094	23385	243,0	9780
	Cretaceous	>50	10	37	565	192	3338	77	1320
Crimea Plain	Danian-	50-120	3-35	23	439	234	4042	16,2	198
	Paleocene	50	<10	1	19	18	278	14	183
	Lower	50-140	3-100	40	877	260	4872	33,1	577
	Cretaceous	>50	<10	3	19	34	197	22	419
Rion artesian basin	Neocomian	35-100	1-100	26	380	273	5115	--	--
Kurinian and Kusur-Divich-insk artesian basins	Apsheron	35-100	1-100	10	69	117	1110	33,2	377
	Productive mass	35-100	10-200	13	237	77	1358	22,0	460
Totally on sedimentary systems		35-150	1-200	342	7448	2568	51163	473	13539
	including	>50	<10	106	2170	634	12412	229	4110

occur over most of the region and in aquifers which lie at a depth of 100-500 m. The East European platform includes the Baltic and Ukrainian shields, large blocks of Pre-Paleozoic basement composed of crystalline rocks. They contain water in fissures in the weathered zone, but have no potential for geothermal purposes.

Hydrogeothermal storage potential

The assessment of thermal water resources with greatest potential in the regions of the European territory of the former USSR was made using the procedure suggested by Shpak (Kulikov & Mavritsky, 1984), taking into account geological and economic parameters and the various production techniques (i.e. flowing or pumping regimes, maintenance of hydrostatic pressure (MHP) through reinjection of the thermal water after use into the rocks). The results of the assessment are given in Table 2.

It should be noted in conclusion that the European part of the former USSR and adjacent regions are rich in geothermal energy. Part of this energy is already used (e.g. Pre-Caucasus, Rioni trough, Crimean Plain, etc.). The prospects for using thermal waters for heating and power utilization may increase considerably through the use of heat pumps, thus allowing the development of low temperature waters which are widely distributed over the area, as well as through the intensive production of thermal water using MHP, which provides a solution to the problem of environmentally safe disposal.

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A CONTRIBUTION TO THE HYDROGEOTHERMICS OF GROUNDWATER SYSTEMS IN EGYPT

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INTRODUCTION

Egypt is located in the arid zone at the most northeastern part of Africa. While about 97% of its population is living on 4% of the land in areas depending on Nile water, the groundwater is the only resource available for multipurpose development in the areas away from the Nile Valley, where there is insufficient rain. Based on the regional groundwater setting in Egypt, the following major groundwater systems can be defined (Figure l):

- The Western Desert System
- The Eastern Desert and Sinai Systems
- The Nile Basin System
- The Coastal Plains System
- The Wadi El Natrun System.

For the purpose of this presentation, and considering groundwater with temperatures higher than the mean annual daily atmospheric temperature to be of a thermal nature, only the following systems will be dealt with:

1. THE WESTERN DESERT SYSTEM
2. THE EASTERN DESERT AND SINAI SYSTEMS.

Hydrogeological records of groundwater in the two systems indicate that the thermal water sources are observed in wells tapping the deep horizons of the Nubian Sandstone aquifers and natural springs emerging from fault zones or joint systems in carbonate rocks overlying, unconformably, the Lower Cretaceous aquifers.

THE WESTERN DESERT SYSTEM

This system underlies the whole of Egypt's Western Desert except for the narrow coastal zone along the Egyptian shores of the Mediterranean Sea.

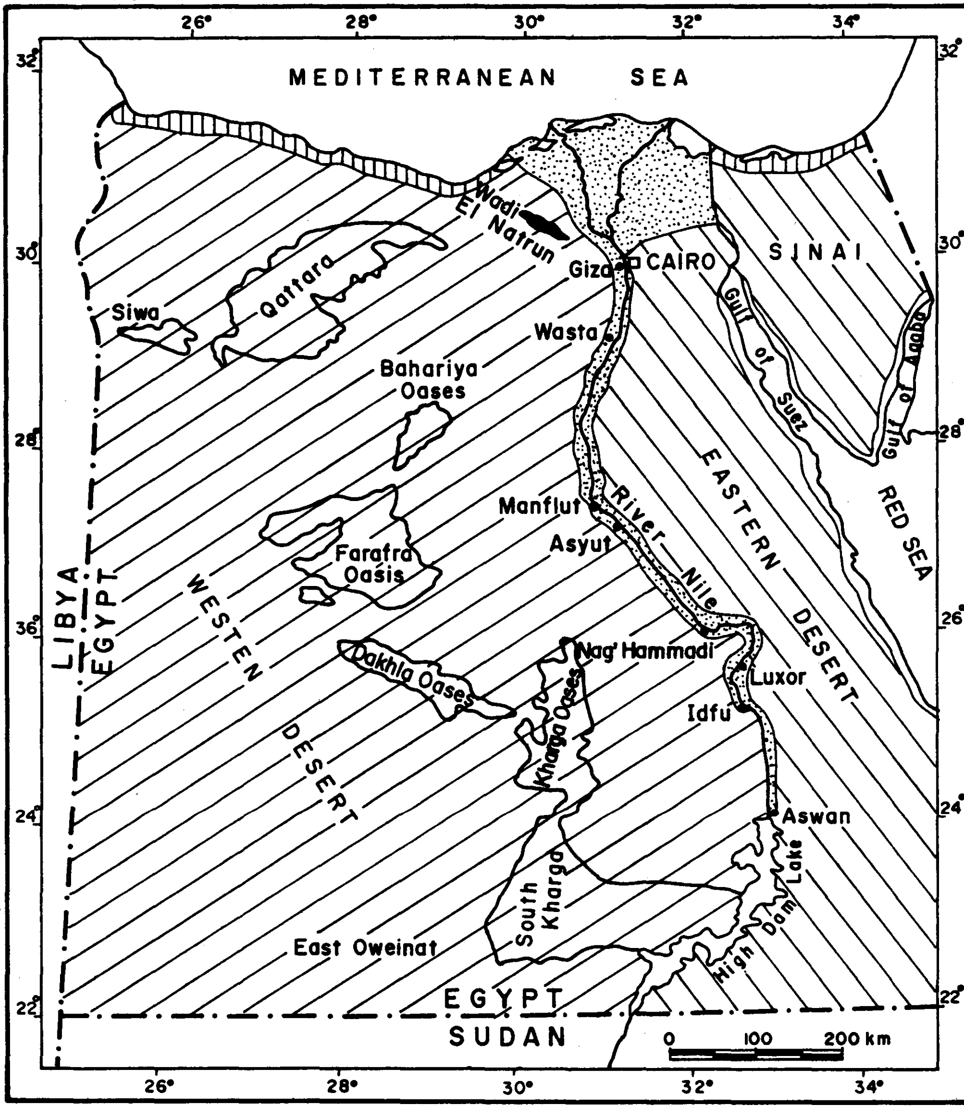

Figure 1: Groundwater systems location map.

Nile Basin System

Western Desert System

Eastern Desert and Sinai System

Coastal Zone System

Wadi El Natrun System

Topographically, this vast area is remarkably uniform and lacking in variety. It consists, for the most part, of vast nearly level plains that are dotted with small hills and broken here and there by cliff-like escarpments, shallow-depressions and flat topped plateaux, with exceptional highland forming one or two mountains.

From a climatological point of view this area is a typical desert region, characterized by a very dry and hot climate. The absolute maximum temperature is 50°C while the minimum is zero. The relative humidity has a mean value of 4% in winter and 27% in summer. The rainfall is very low, ranging from zero to about 15 mm/year.

The previous description of the Western Desert reflects the comparatively simple and uniform geological structures in this area. Sediments of Paleozoic, Mesozoic and Tertiary age dip gently to the north and overlie the Precambrian Basement Complex. Sediments become progressively younger in age from the southern boundary to the shores of the Mediterranean Sea. Superimposed on this great northward dipping monocline are various structural trends, including surface folds, faults, and subsurface gravity anomalies.

The Western Desert Nubian system, which is one of the three groundwater provinces of the Nubian Sandstone in Egypt, underlies the whole of this Western Desert and in a broad sense extends to the high massifs of Ennedi, Eridi, Tibesti, Tummu, and the Hammadas of Fezzan in the West. The southern limits of this system may be taken as the northern confines of Darfour and Kordofan in Sudan.

This aquifer consists of a thick sequence of coarse, clastic sediments of sandstone with intercalations of sandy clay, shale, and clay. The more clayey impermeable beds restrict the vertical movement; thus aquifer zones are formed within the Nubian Sandstone which comprises a regional single aquifer complex. It increases in thickness from south to north with a proven thickness of 800 metres in Kharga Oasis, 1500 metres at Dakhla Oasis and about 1800 metres in Bahariya Oasis. In Farafra Oasis the total thickness of this complex is estimated to be 2800 metres and gets thicker to the north to a maximum recorded 3500 metres at the Desouky exploratory oil well south of Siwa.

In general the Western Desert Nubian Sandstone formation is characterized by being fresh water bearing throughout the whole section except for the very northern part where a highly saline water occupies the highly porous formation. The fresh water (200 to 500 ppm) from this system is only exploitable in the depressions where its water is characterized by an artesian flow with a head considerably above ground level, or semi-artesian within the reach of reasonable lift and in the areas where the Nubian Sandstone outcrops, as in East Oweinat.

According to the piezometric map prepared by Ezzat (1974) (Figure 2), the groundwater flows in general from the Eridi and Ennedi region on the borders of the Chad basin, in a southwest - northeast direction, discharging mainly at the depressions of Kharga, Dakhla, Farafra, Siwa and Qattara.

For more details, each of the Western Desert Depressions will be discussed independently, namely: (1) Qattara Depression; (2) Bahariya Oasis; (3) Farafra Oasis; (4) Dakhla Oasis and (5) Kharga Oasis.

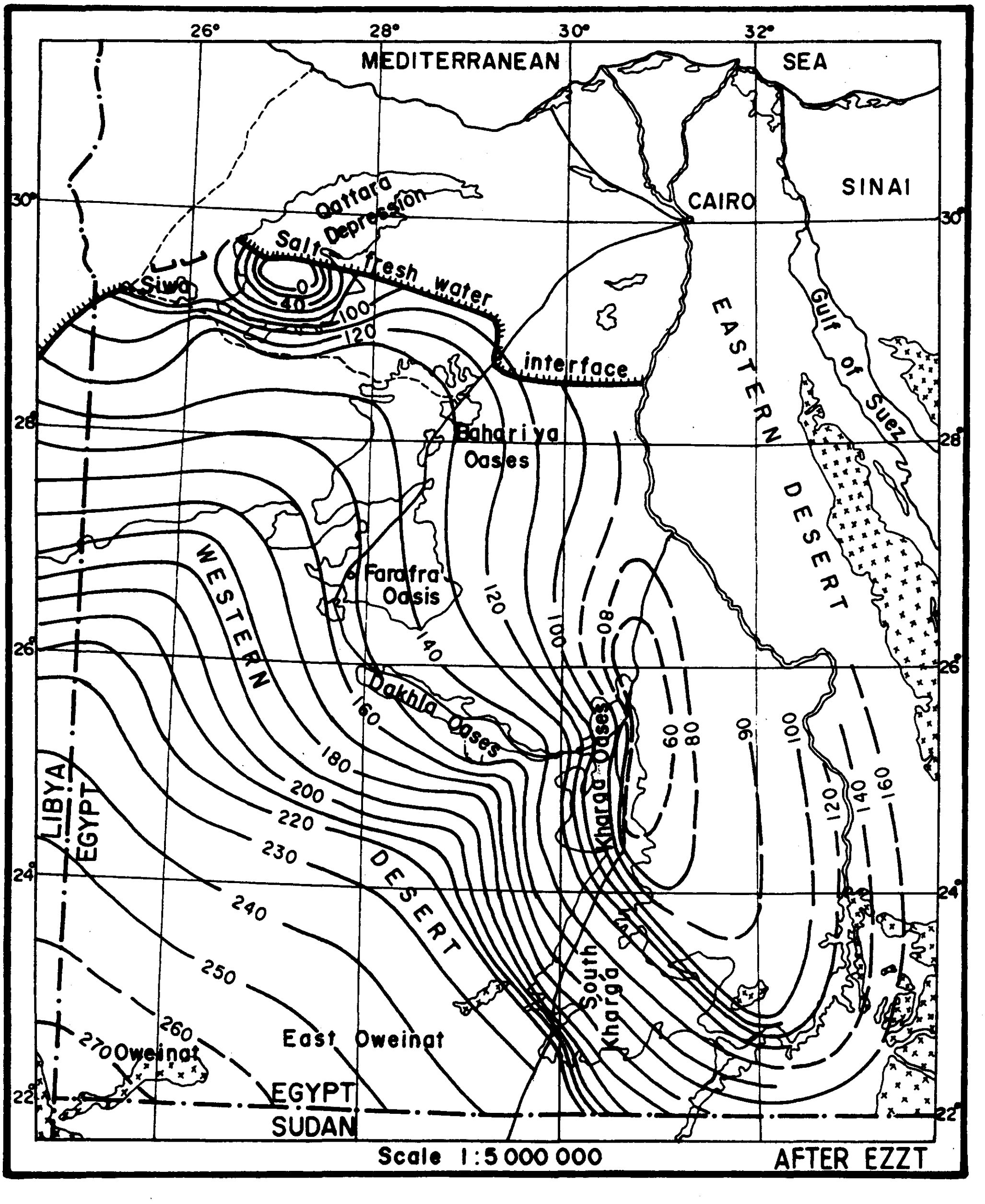

Figure 2: Piezometric map of the Nubian aquifer system.

QATTARA DEPRESSION

The Qattara depression is the largest of the Western Desert depressions and is located in its northern part. It is constituted of subsidiary lows forming, ultimately, a unified complex depression. The lowest part of its floor, which is located in its southwestern zone, is 145 m below mean sea level. The depression covers an area of 95000 km^2, extending roughly ENE-WSW for about 300 km and sustaining variable breadths which increase in a westward direction to reach a maximum width of roughly 245 km. This depression is characterized by being uninhabited except for about 100 people living in Qara. A lot of consideration is being given to a hydroelectric power project, as a result of which sea water entering the depression would be maintained at a level of -80 m.

The Qattara Depression is carved into horizontal layers of Miocene and Eocene sediments. Sandy and clayey layers of Lower Miocene age (Moghra Formation) form the bottom and the surroundings of the northeastern part of the depression, while the calcareous and clayey sediments of the Middle and Upper Eocene and Oligocene predominate in its southwestern part. The northern border is formed by a steep escarpment which is covered by the Marmarica Calcareous formation of Middle Miocene age, which increases in thickness towards the Mediterranean coast. The genesis of the Qattara Depression was reported to be due to the interaction of tectonics, wind erosion and groundwater fluctuations.

Due to the fact that the depressed zone, between Jaghbub Oases (Libya) in the west and the Moghra Lake in the northern part of the Qattara Depression, forms the topographically lowest area of Egypt (5 to 133 m below sea level), this zone acts as final base level for the groundwater of the Western Desert System. Groundwater reaching the floor of the depression of this zone evaporates forming a series of salt marshes locally named Sabakhas. The water evaporating in Qattara is therefore considered to be a loss. In the future, sea water passing through the electrical power plant will form a lake in the depression. Accordingly, the head of water in the lake will counteract the flow of the groundwater and stop the losses.

Several deep test-drillings have been carried out within the depression to investigate the possibility of oil and/or natural gas occurrences. One of these wells is the Kifar well which was drilled down to the basement at 3000 m. This well was completed as a water well cased at 9 5/8 inches and drilled to a total depth of 1246 m. Only the interval from 1170 to 1178 m below ground surface was gun perforated to develop the upper part of the Nubian formation. The lithostratigraphical log of this well is shown in Figure 3. Water was flowing in 1983 from the Kifar well at a temperature of 65°C, thus recording the highest temperature for water flowing from the Western Desert System. The well was tested in 1988 at 400 m^3/hour and a water analysis showed that the total dissolved solids content is 600 ppm.

BAHARIYA OASIS

Bahariya Oasis is located to the south of the eastern flank of the Qattara Depression. It is approximately 350 km southwest of Cairo and about 200 km to the north of Farafra Oasis.

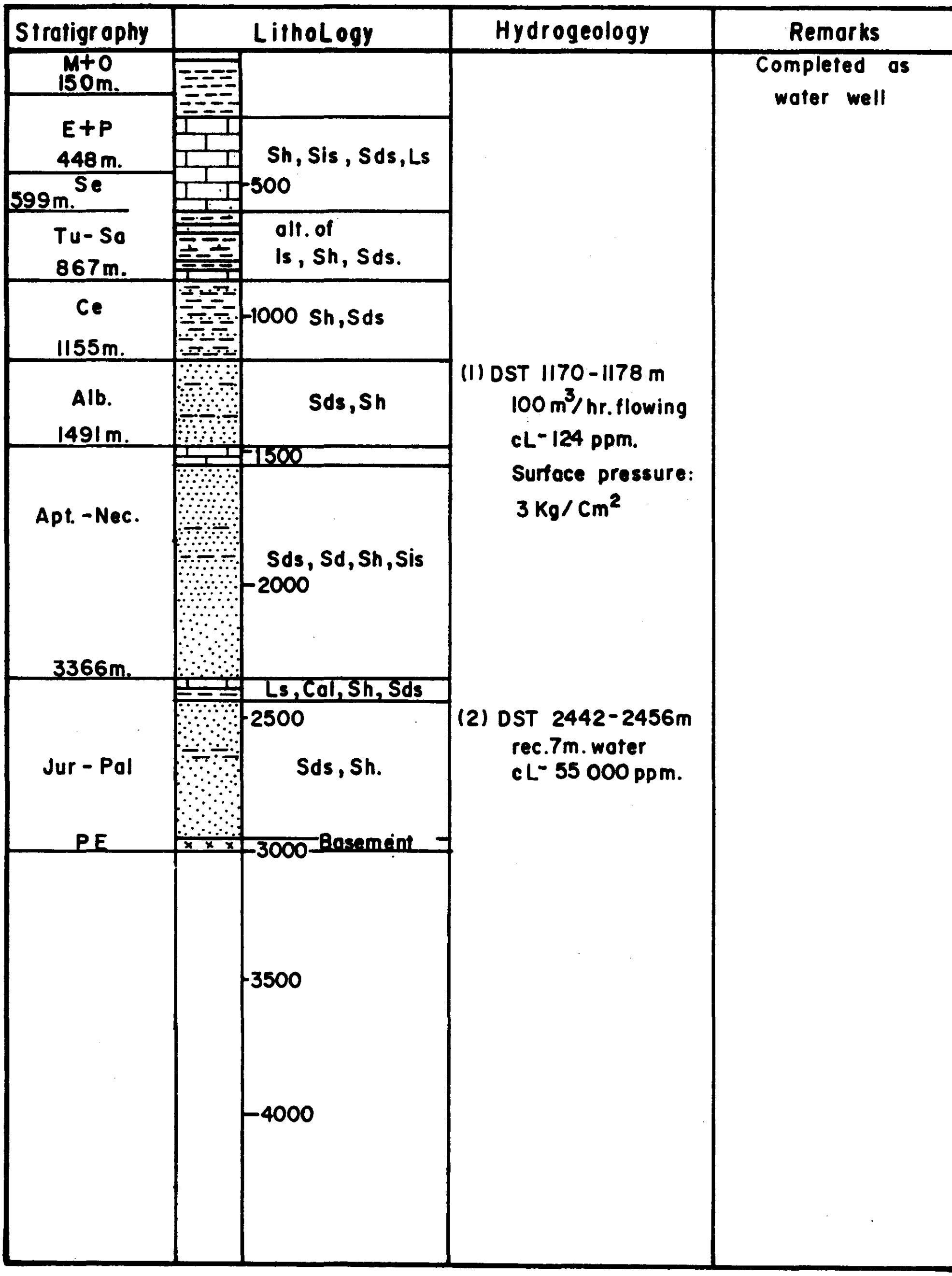

Figure 3: Kifar well hydrogeological log.

The depression of Bahariya is entirely surrounded by mostly steep escarpments. Its shape is elliptical, with a 200 km long northeast-southwest axis and a 48 km axis at its widest part. Its area is 2250 km^2.

The folding, faulting and varying rock resistance have controlled the details of the topography of this area. The completion of an exploratory oil well in the Oasis in 1957 showed that the Precambrian Basement Complex is at a depth of 1820 m. The Nubian Sandstone overlies the basement. The floor of the depression is built up of Bahariya Formation, which is assigned to the Cenomanian or the upper part of the Nubia Formation. The Bahariya Formation is overlain westwards by the ElHefhuf Formation (Campanian), the Chalk Formation (Maestrichtian). To the south of ElGedida area, the Oligocene Radwan Formation crops out. Turonian - Santonian beds of dolomitic limestone and sandstone overlie the Cenomanian on the plateau and on the synclinal ridges in the depression. In the north and northeast part of the area Middle Eocene limestone overlies the Cenomanian (Figure 4). The large hills on the northwest part of Bahariya are capped with columnar basaltic lavas (Oligocene). The greater part of the basalt occurs as an extrusive capping of horizontal Cenomanian beds.

Bahariya Oasis originally depended on some natural springs that owe their existence to structural events; the criss-cross pattern of folding and faulting created the condition favouring the upward movement of groundwater to the surface. One of these springs in Bahariya Oasis is the Bishmu Spring, which is located in the northeastern part of the Oasis, flowing at 31,6°C. Table 1 shows temperature, pH, electrical conductivity and total dissolved solids of some Bahariya Oasis wells.

Recent deep drilling at Qabala, in the northeast, and ElHeiz in the southeast of Bahariya Oasis, indicated that groundwater from two wells completed to a depth of 1000 m is flowing at a temperature reaching 45°C. Figure 5 shows a lithological log of ElHiez deep well.

FARAFRA OASIS

The depression occupied by Farafra Oasis is the second largest depression in the Western Desert. It is roughly rectangular in shape with its long axis trending in a northwest-southeast direction. Unlike Bahariya, the Farafra Depression is not entirely surrounded with escarpments; on the south and southeast side, the floor merges imperceptibly with that of the plateau. The depression is roughly 12000 km^2 in area.

The outstanding geomorphic features in Farafra are the innumerable erosional remnants carved out of white chalk. Turonian-Santonian dolomitic limestones and sandstones (Nubian Sandstone series) crop out locally in the northern part of Farafra Oasis. Maestrichtian chalk overlies these sediments. The Upper Paleocene Esna shale overlies the chalk, and is well exposed on the east and west escarpments. Lower Eocene limestone overlies the Esna Shale, forming the plateau surface. A gentle northeast-southwest trending anticline occurs in the northern part, while the east escarpment is controlled by local anticlines, synclines, joints and faults (Figure 6).

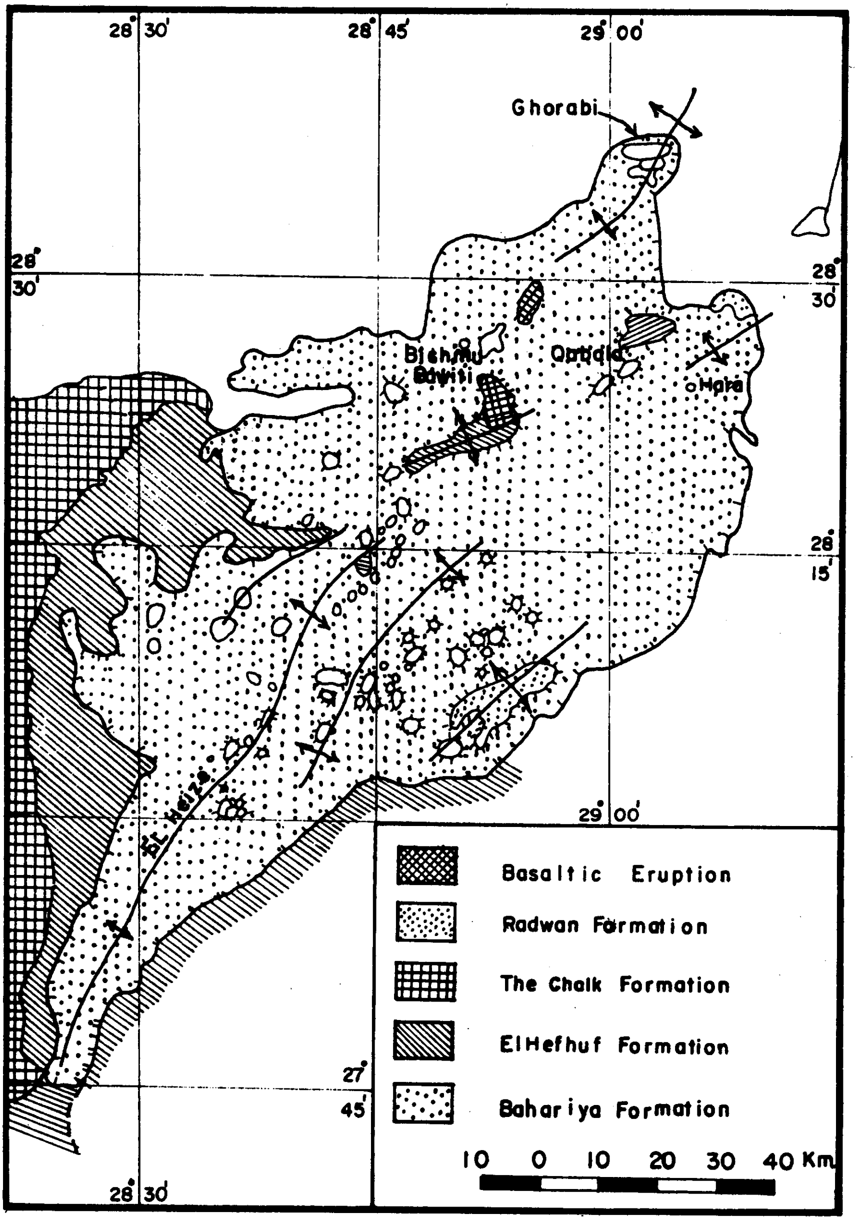

Figure 4: Bahariya Oasis geological map.

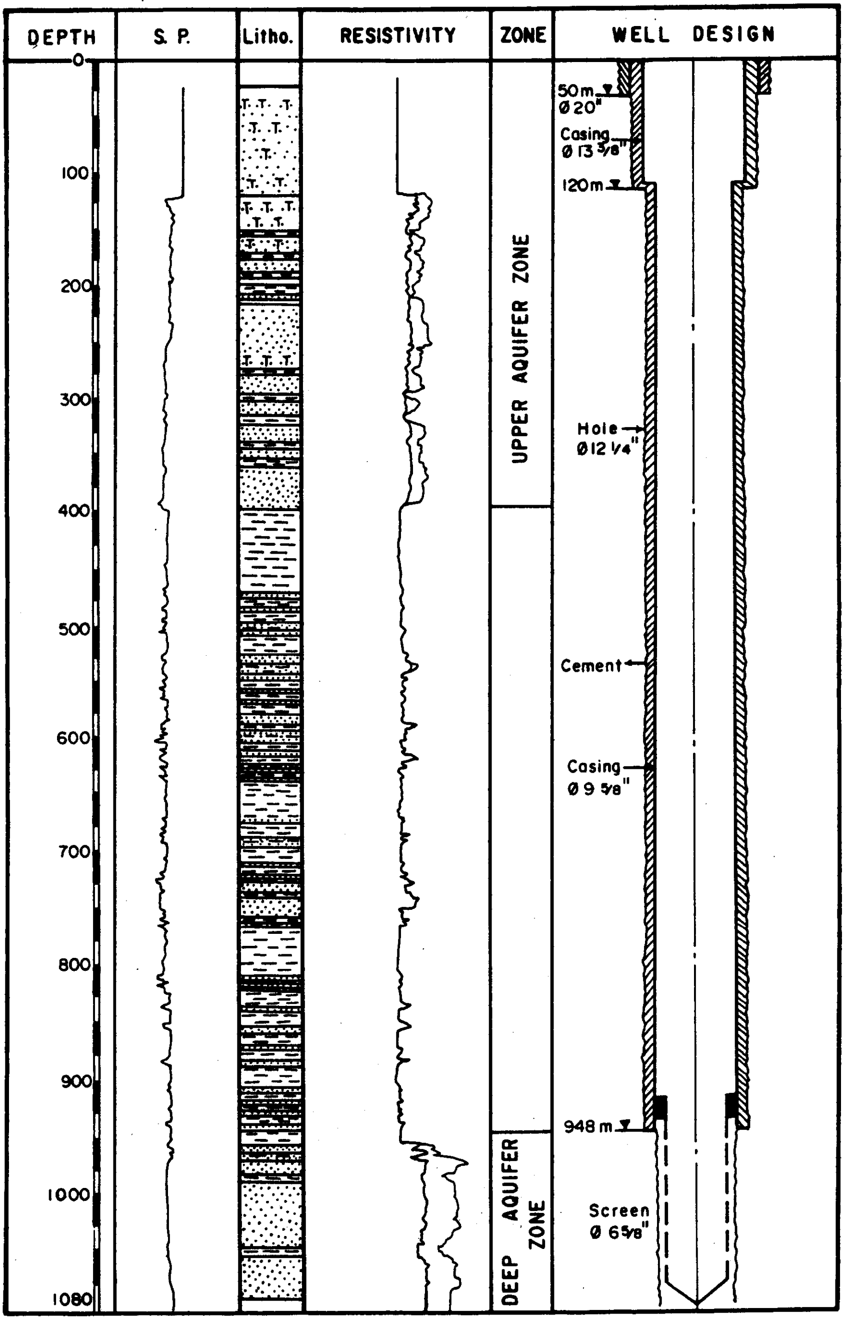

Figure 5: El Heiz (deep) well at Bahariya Oasis (drilled by REGWA Co., May 1987).

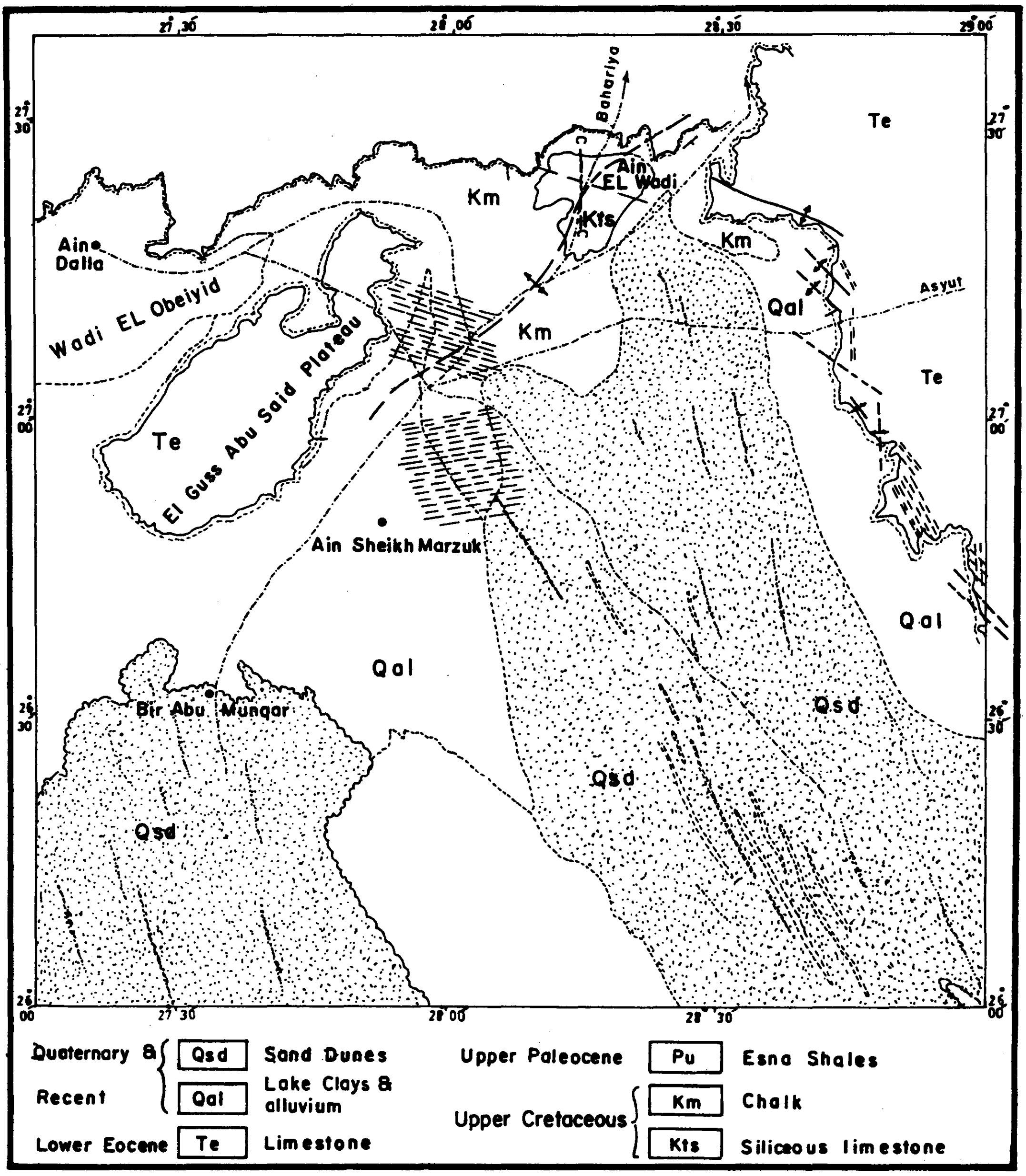

Figure 6: Geological map of Farafra Oasis (scale - 1:1 000 000).

Table 1: Bahariya Oasis well data.

Source	Depth (m)	Temp. (°C)	pH	EC (μmhos/cm)	TDS (ppm)
New Wells:					
ElQasa 2	800	40,0	7,6	370	240
Measra (Airport)	800	29,0	7,6	240	156
ElQasr (Tebinya)	**	36,0	7,6	370	240
Mandisha 6	784	41,0	7,6	370	243
ElBawity (Makana)	692	40,5	7,6	400	260
ElBawity (Tahkima)	816	44,0	7,6	400	260
ElHeiz (Deep)	1000	45,0	7,6	220	143
ElHeiz (Shallow)	200	30,0	7,6	240	156
Ain Gedid	806	40,0	7,6	280	182
Ain ElWadi	804	41,0	7,6	240	156
Old Wells:					
Ain ElBeshmow (Cold)	**	27,0	7,6	370	240
Ain ElBeshmow (Hot)	**	31,6	7,6	220	143

** = unavailable data

Limestone leaky aquifer

Before drilling the first well at the Farafra Oasis in 1965, Farafra as a whole depended on springs that originated along faults and fractures through shales and chalky limestone of Lower Eocene or Maestrichtian age; local moderate outflows of water rise from the artesian water bearing Nubian Sandstone. Thus the chalky limestone, acting as a leaky aquifer, was the only source of water required for all development in Farafra.

It may be worth mentioning that as the mean yearly atmospheric temperature of this area is about 23°C, all springs with temperatures higher than that can be considered thermal springs.

An inventory of the temperature, electrical conductivity and pH values of the water from 67 springs in Farafra was made in 1962 and updated in 1983 for only 40 of them. The result was as follows:

(1) *The water temperature* in 1962 varied from 19°C to 30°C, while in 1983 it varied from 22°C to 30°C.

(2) *Electrical conductivity* in 1962 ranged from 600 to 1200 micromhos/cm with an average

value of 850 micromhos/cm and in 1983 the average was 950 micromhos/cm, an appreciable increase.

(3) *pH values* measured during 1962 ranged from 6,9 to 8,4 with an average value of 7,85, while in 1983 it varied from 7,5 to 8,5 with an average value of 8,03.

The increase of pH value is considered to be due to the release of some dissolved carbon dioxide as a result of an increase in the average temperature. In other words, the pH value has increased as a result of less carbonic acid.

Nubian Sandstone aquifer

The Nubian Sandstone artesian aquifer was first exploited in 1965 when drilling of 10 deep wells started. In Farafra Oasis, all of the wells exploited the second aquifer zone of the Nubian Sandstone system. Only one observation well exploited the first aquifer zone.

Sheikh Marzouk exploratory well was drilled to a depth of 1202 metres and completed to 1003 metres in 1985. It was the first well to tap the third aquifer zone of the Western Desert Nubian Sandstone system at Farafra. This well was the first in which thermal well logging was performed in this area. Data obtained included: lithostratigraphical data (age, formation, depth, columnar section and lithological description) and geophysical log interpretation data (geothermal gradient, average Gamma-ray values, total porosity corrected values from CNL, average resistivity and temperature log) (Figure 7).

Although the full thickness of the Nubian formation has not yet been explored, much basic data have been obtained including:

(1) *Temperature*: The maximum temperatures recorded in 1985 of the water flowing from different aquifer zones were equal to:

   (a) The first aquifer zone: 35,5°C
   (b) The second aquifer zone: 41,3°C
   (c) The third aquifer zone: 45,1°C

   Some temperature records and other data that were collected from some other wells in 1987 are indicated in Table 2.

(2) *Piezometric head* was measured in 1955 and showed that the second and third zones have an average of 43,47 m and 45,06 m above a reference point fixed on the well-head.

(3) *Leakage between aquifers*: No evidence of vertical leakage between two aquifer zones was detected. But in 1985, while testing the third aquifer zone, the static water level of the second aquifer zone instead of dropping as should be the case when leakage occurs, rose 1,13 m from the initial value. It is beyond doubt that the increase of the well-head pressure was due to the transmission of heat through the conduit of the dual well equipment (completion), with the water from the third aquifer zone having a higher temperature.

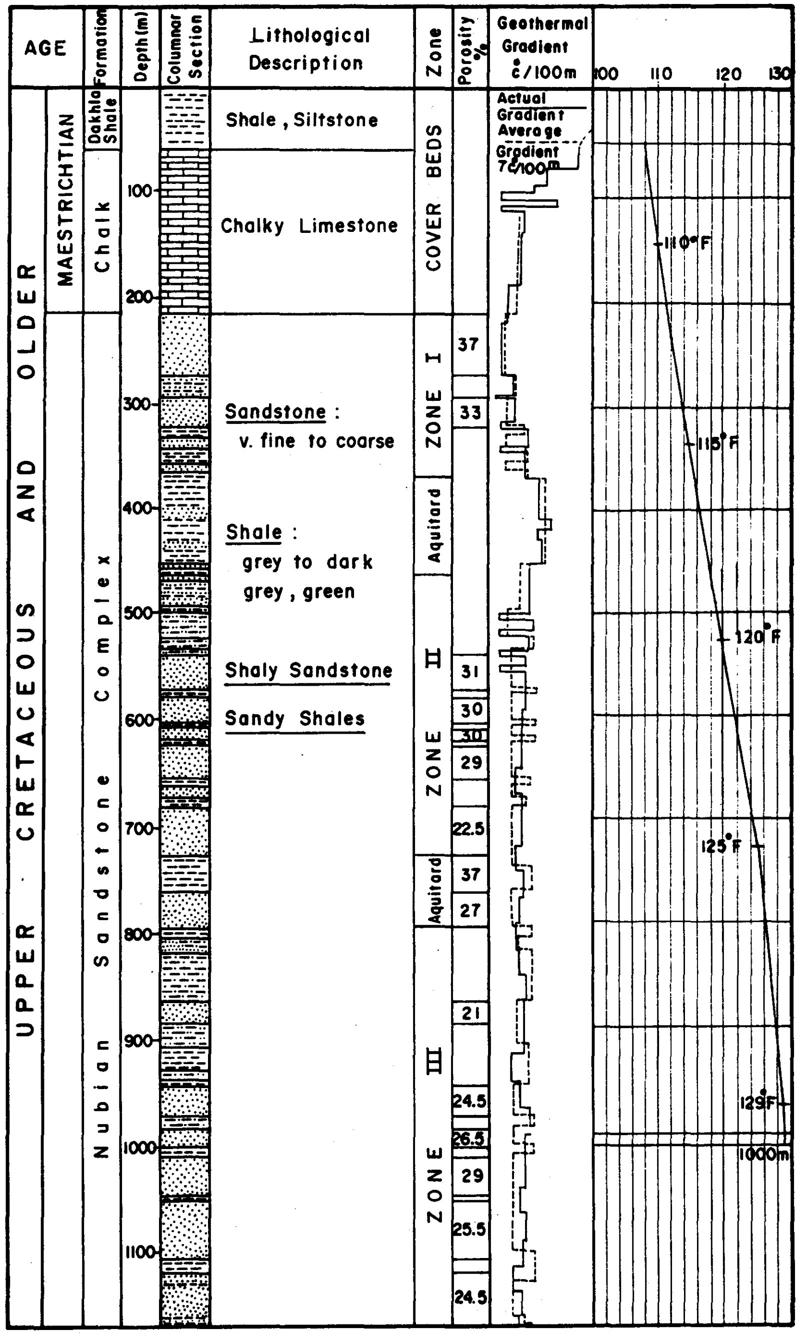

Figure 7: El Sheikh Marzouq exploratory well (Farafra Oasis).

In this system groundwater with a temperature of more than about 22°C is considered to be thermal water. Thermal groundwater in this system occurs as flowing wells tapping the deep Nubian Sandstone aquifer zones (400 to 1200 metres deep) or as natural springs issuing from the overlying fissured carbonate rock of Upper Cretaceous age.

Table 2: Farafra Oasis well data.

Source	Depth (m)	Temp. (°C)	pH	EC (μmhos/cm)	TDS (ppm)
New Wells:					
ElBalad (School)	804	37,0	7,6	250	162
Regwa (Camp)	800	28,0	7,6	300	195
Well No. 6	800	37,0	7,6	280	182
Well No. 19	800	41,0	7,6	238	155
Well No. 20	800	42,0	7,6	280	182
Well No. 17	800	37,0	7,6	250	162
Sheikh Marzouq	1200	45,1	7,6	250	163
Old Wells:					
Ain ElBalad	**	27,0	7,6	370	240

** = unavailable data

DAKHLA OASIS

The Dakhla Oasis is a depression lying with its long axis oriented in a WNW-ESE direction. It is bounded in the north by a remarkable topographic feature in the form of a bold precipitous escarpment facing south and running more or less irregularly for at least 200 km in an easterly direction to the Kharga Oasis. It is composed of an Upper Cretaceous - Eocene shales and carbonates complex (Figure 8).

Structurally, the Dakhla Oasis is a major syncline which is dominated by sinuous-type folds of alternating minor anticlines and synclines within the major syncline.

The floor of the depression is covered by the red clay bed which forms the uppermost member of the Nubian Sandstone formation and confines the lower sandstone aquifer system. The Nubian Sandstone aquifer's thickness ranges from 900 m, in the eastern part of the Oasis, to 1800 m in its western part. Although most of the wells in Dakhla Oasis are flowing at a temperature higher than 30°C the greatest thermal anomaly is observed at well Mut 3, located at the centre of the Oasis. This well was completed to a depth of 1200 m and is flowing at a temperature of 42°C.

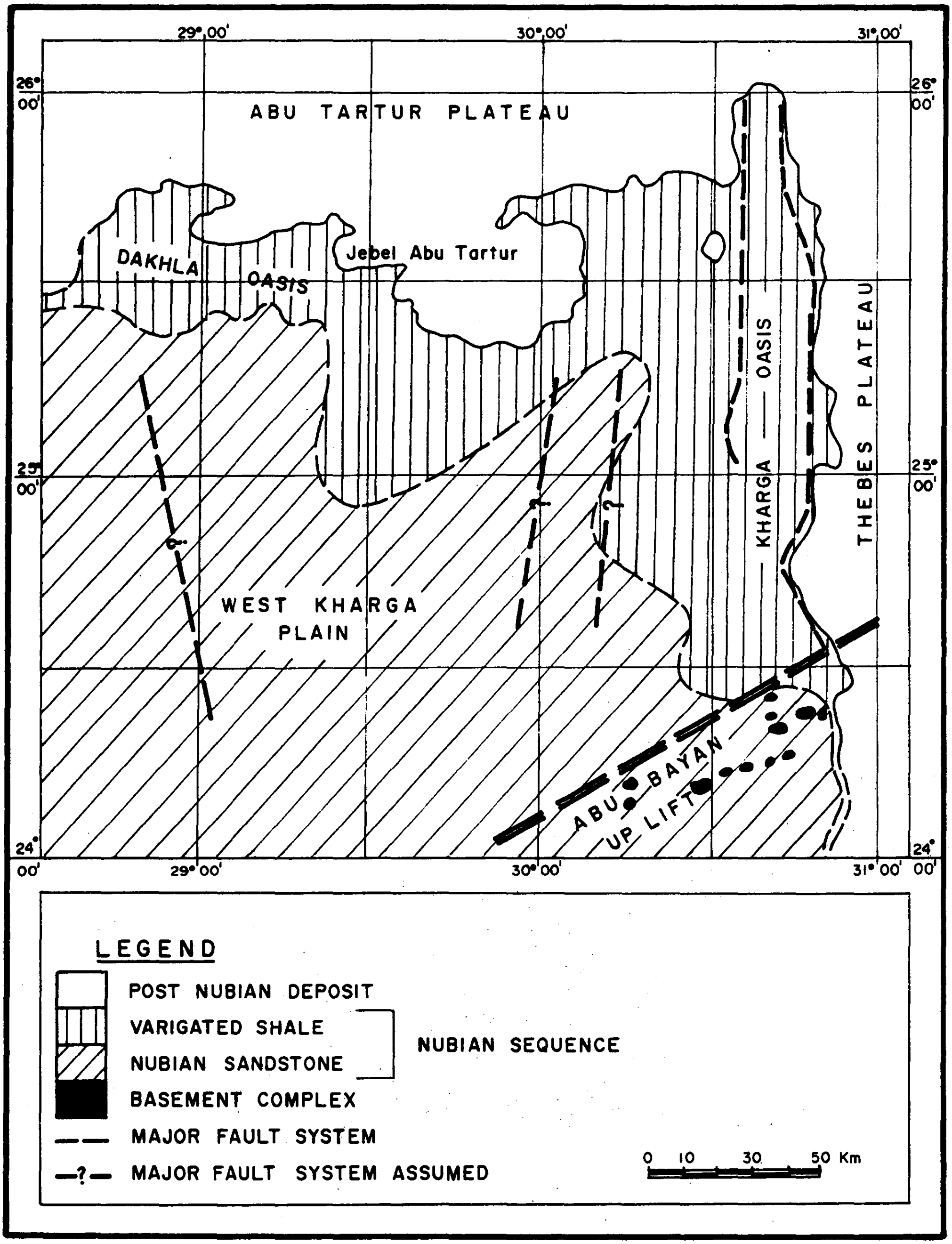

Figure 8: Schematic geological map of Dakhla and Kharga Oases.

Table 3: Dakhla Oasis well data.

Source	Depth (m)	Temp. (°C)	pH	Residue (ppm) at 180°C	HCO_3 ppm	epm	Cl ppm	epm	SO_4 ppm	epm	Ca ppm	epm	Mg ppm	epm	Na ppm	epm	K ppm	epm	Fe ppm
New wells :																			
Balat 2	627	35,5	6,6	150	47,6	0,76	34,0	0,95	33,0	0.69	8,8	0,44	7,8	0,64	19,0	0,82	22,0	0,57	0,74
Hindaw 2	779	30,0	6,7	130	43,9	0,70	28,0	0,78	20,0	0,42	10,4	0,52	7,3	0,60	13,0	0,56	20,0	0,52	**
Maasara 2	517	35,0	6,9	220	41,0	0,66	62,6	1,75	62,5	1,31	24,0	1,20	13,6	1,12	27,0	1,16	11,0	0,29	0,24
Asmant 2	762	32,0	6,5	270	39,0	0,62	70,0	1,96	57,5	1,21	28,8	1,44	11,0	0,92	29,0	1,25	7,5	0,20	**
Mutt 2	800	37,0	6,4	260	36,6	0,59	68,0	1,90	58,5	1,23	27,0	1,36	11,0	0,92	29,0	1,25	7,5	0,20	1,50
ElRashda 3	500	34,0	6,6	215	36,6	0,59	54,0	1,51	49,5	1,04	20,0	1,00	9,7	0,80	25,0	1,08	10,0	0,26	1,50
ElKala-moun 2	584	36,0	6,4	280	36,6	0,59	76,0	2,13	60,0	1,26	27,0	1,36	10,2	0,84	33,5	1,44	11,0	0,29	0,56
Budkhulu 2	795	34,0	6,3	210	39,0	0,63	48,0	1,34	46,8	0,98	20,0	1,00	8,3	0,68	23,5	1,01	10,0	0,26	1,60
ElMawhoob 2	834	35,0	6,7	210	43,9	0,70	46,0	1,29	57,5	1,21	23,0	1,16	10,0	0,84	21,5	0,92	10,0	0,26	0,68
Old wells :																			
Abu Gobran, Balat	**	28,0	7,0	190	66,0	1,12	56,0	1,57	15,0	0,32	8,8	0,44	7,2	0,59	21,0	0,90	19,3	0,50	2,00
ElShiekh Hassan, ElRashda	**	29,0	6,4	163	52,5	0,84	60,0	1,68	42,5	0,89	19,0	0,96	14,9	1,22	31,3	1,35	9,7	0,25	7,70
Ons ElAin, Mutt	**	30,0	6,7	340	42,5	0,68	116	3,27	100	2,10	49,6	2,48	17,0	1,39	40,0	1,72	7,7	0,20	7,70
ElAbeed, ElMawhoub	**	36,5	6,7	210	75,5	1,21	52,0	1,46	50,0	1,05	16,8	0,84	6,3	0,52	38,0	1,64	7,7	0,20	5,80

(** = unavailable data).

Table 4: Kharga Oasis well data.

Source	Depth (m)	Temp. (°C)	pH	Residue (ppm) at 180°C	HCO_3 ppm	epm	Cl ppm	epm	SO_4 ppm	epm	Ca ppm	epm	Mg ppm	epm	Na ppm	epm	K ppm	epm	Fe ppm	TH as CaCO ppm
New wells :																				
Mahariq 7	718	31,0	**	368	324	5,31	68	1,92	11,0	0,22	16,0	0,80	21,0	1,73	98,0	4,30	22,0	0,60	1,70	128
Kharga Gomhoria R	629	39,0	**	374	130	2,13	38	1,07	29,0	0,60	14,4	0,72	21,4	1,76	21,0	0,91	24,0	0,61	0,30	124
Naser 1	396	39,0	7,3	210	114	1,84	59	1,66	13,0	0,28	15,0	0,75	13,0	1,07	31,0	1,35	31,0	0,79	**	**
Bulaq 4	666	38,0	7,2	248	108	1,77	80	2,26	13,0	0,28	21,0	1,04	14,0	1,15	39,0	1,70	26,0	0,76	1,00	**
Baris 9	651	36,0	7,2	360	98	1,61	103	2,90	53,0	1,10	26,0	1,30	12,0	1,00	64,0	2,78	29,0	0,74	4,50	**
Khalga 24	274	31,0	**	202	120	1,97	44	1,24	**	**	12,0	0,60	26,8	2,20	15,0	0,56	34,0	0,87	1,90	140
Bulaq 4A	387	32,0	7,1	662	88	1,44	220	6,20	132	2,75	58,0	2,89	38,0	3,12	92,0	4,10	36,0	0,92	**	**
Old wells :																				
Ain ElBoch	**	31,0	**	292	108	1,77	96	2,70	**	**	22,4	1,12	17,5	1,44	20,0	0,87	34,0	0,87	Nil	128
Ain ElBidal	**	31,0	**	260	144	2,36	106	2,98	**	**	20,8	1,04	21,4	1,76	20,0	0,87	32,0	0,87	Nil	140

(** = unavailable data).

Ein ElGabal, located in the northeastern part of the Oasis, produces water from a faulted zone with a temperature of 40°C.

Table 3 shows water temperature and chemical analyses of some wells in Dakhla Oasis.

KHARGA OASIS

The Kharga Oasis has a basin-like form, elongated from north to south, and surrounded from the east and north by a step-like escarpment composed of rocks of Upper Cretaceous and Eocene ages, 300 metres thick. The depression floor is covered by variegated shales which cap the underlying Nubian Sandstone aquifer, the thickness of which ranges between 200 m in the southern part of the Oasis to 800 m at its northern periphery.

Structurally, the Kharga Depression is an anticline, interrupted by N-S oriented faults along its contact with the eastern plateau and forming a relatively impermeable boundary to groundwater flow. A fault which cuts across the central part of the depression also acts as a barrier to the flow.

Data relating to water temperatures and chemical analyses of some waters in Kharga Oasis are shown in Table 4. Thermal groundwater with a temperature of more than 40°C is recorded at some wells in Ginan and Garmashein (Figure 8).

THE EASTERN DESERT AND SINAI SYSTEM

Topographically the Eastern Desert and Sinai Peninsula, excluding the lowlands that form the Red Sea and Mediterranean coastal plains, are characterized by a highly rugged mountainous relief and high elevated plateaux. The location of this system is shown in Figure 1. Hydrogeologically it is subdivided into two sub-zones: sedimentary zone and igneous zone. As there is no record of thermal waters in the igneous zone, only the sedimentary zone will be considered.

The Sedimentary Zone encompasses the whole of North Sinai Governorate, except the coastal area, and part of the South Sinai, mainly located (Figure 9) between the igneous mass and the coast. In the Eastern desert it forms mainly the high plateau that fringes the eastern boundary of the Nile Valley and the very northern part of the Eastern Desert, overlooking the Gulf of Suez.

The thickness of the sediments in some cases exceeds 6000 m. In general it can be subdivided from a hydrogeological point of view into two main water bearing formations:

Nubian Sandstone Formation

The Nubian Sandstone aquifer underlies the sedimentary formation of the Eastern Desert. Development and exploitation of this aquifer is so far limited. Test drilling in the areas of Wadi Qena and Wadi ElMatuli indicated that the Nubian aquifer system attains a thickness ranging between 400 and 650 metres, under confined conditions. Results from test wells showed that

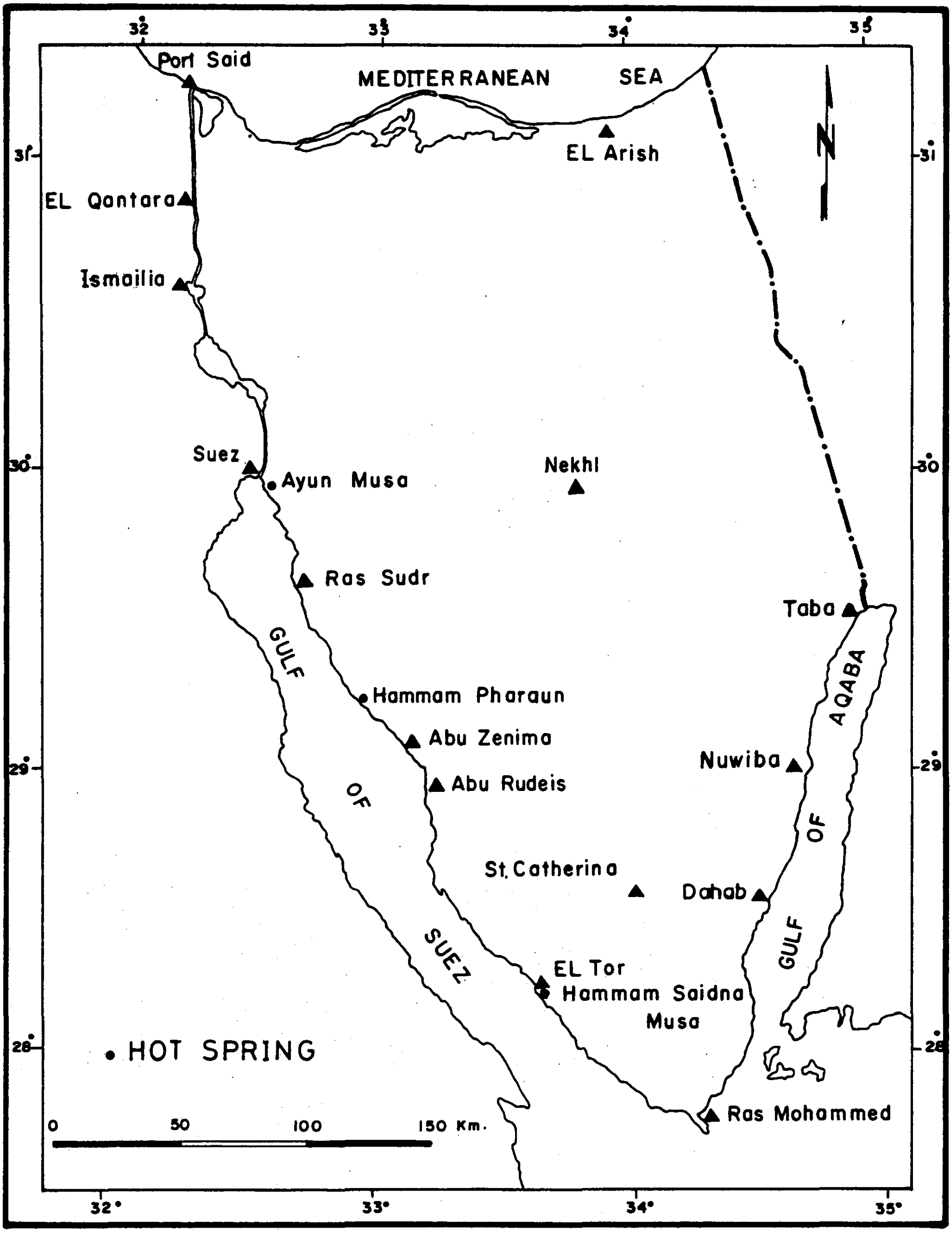

Figure 9: Sinai location map.

naturally flowing wells occur only in areas of low topographic elevations. Such wells are flowing at a rate ranging between 60 and 100 m^3/hr. Chemical analyses indicate that groundwater salinity of the Nubian aquifer in these two wadis varies between 1000 and 2800 ppm. It is believed, due to the observed piezometry, that the aquifer's recharge area is located at its outcrops along the eastern Red Sea mountain ranges. No temperature records for these wells are yet available.

The Sinai Nubian Sandstone forms the aquifer for the Hammam Sayedna Musa spring at El Tor, Hammam Faraon on the eastern coast of the Gulf of Suez, Ein ElSokhna on the western coast of the Gulf of Suez in the Eastern Desert, Ayun Musa on the Gulf of Suez coast in Sinai and Helwan Spring in the vicinity of Cairo. Table 3 shows the water analyses of these springs and the following is a brief review of each:

Hammam Sayedna Mosa Spring: This spring is located at the foot of Gabal Hamman Sayedna Mosa, five kilometres to the north of ElTor and flows at a temperature of 33°C from the faulted Miocene rocks outcropping in the area. The source of this hot water is a deep aquifer underlying the area, probably the Sinai Nubian Sandstone.

Hammam Faraon Springs: These springs which are about 100 kilometres to the south of Suez on the eastern coast of the Gulf of Suez, are flowing from the shore cliff of Gabal Hammam Faraon. The water issues from faulted dolomitic Eocene limestones at a temperature of 72°C. It is believed that the origin of this hot water is the Nubian Sandstone aquifer at depth and connected to the surface through a major fault system. Hammam Faraon water is mineralized with a total dissolved solids of about 15000 ppm. A detailed water analysis is shown in Table 5.

Table 5: South Sinai well data.

Source	Depth (m)	Temp. (°C)	pH	EC (μmhos/cm)	TDS (ppm)	SO_4 (mg/l)
Hammam Faraon Spring	**	63,0	7,6	11500	7495	700
AbuZenima Area, Elseeh well	**	23,0	7,6	2700	1755	**
AbuZenima Area, ElNassub well	**	25,0	7,6	1300	845	**
Hammam Sayedna Mosa Spring	**	33,0	**	**	9000	**

** = unavailable data

ElSokhna Spring: This spring is located at the foot of the raised faulted block forming Khashm ElGalala scarp. The spring discharges water of 33°C at a rate of 1800 m^3/day. It was reported that the hot water of the ElSokhna Spring is formed by deeply circulated Eastern Desert Nubian water rising through the fissures and fractures under high hydrostatic pressure and mixing with normal sea water.

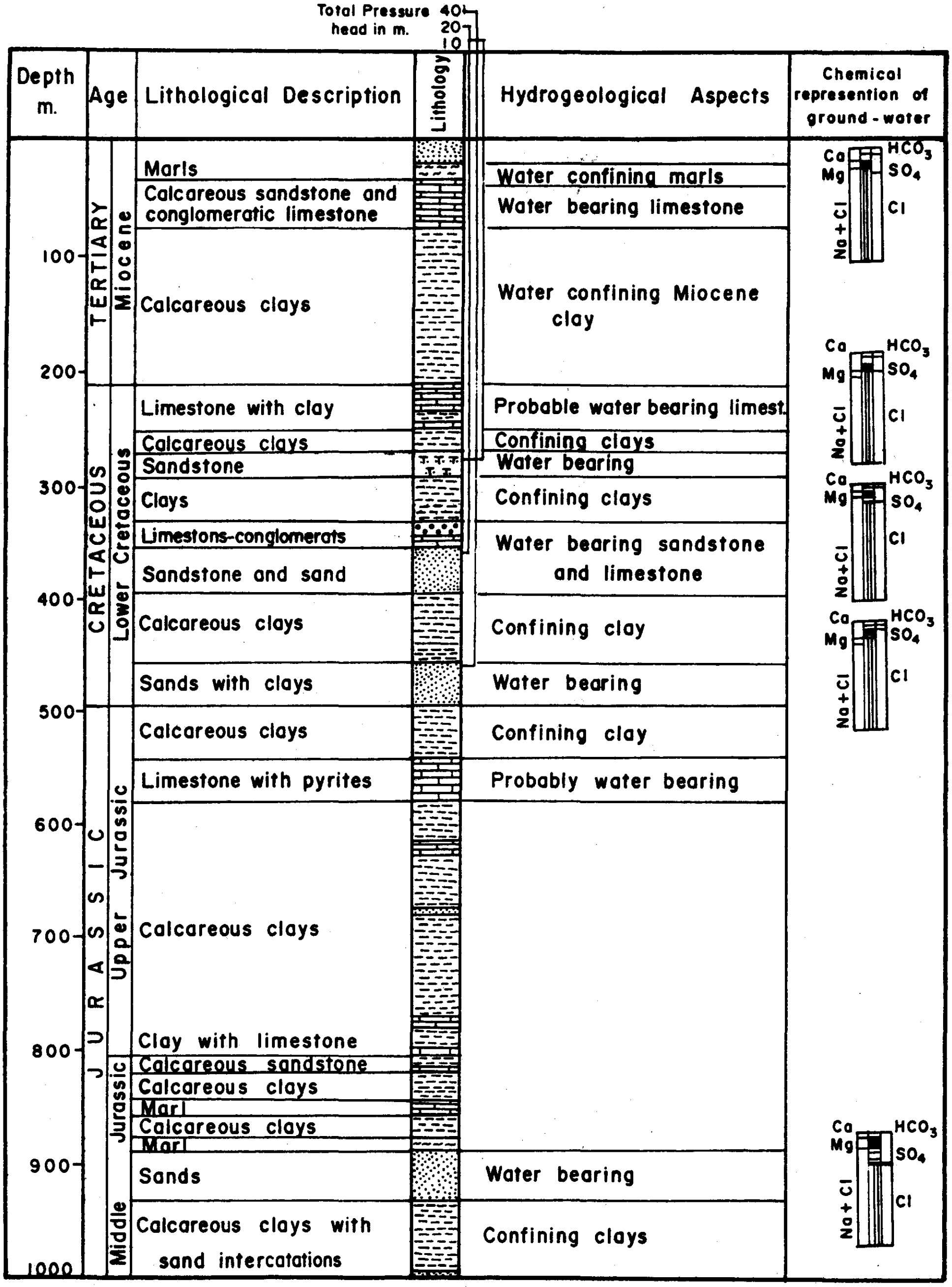

Figure 10: Composite hydrogeological section for the Ayun Musa area.

Ayun Musa: The Quaternary formation at Ayun Musa area is not acting as an aquifer. Therefore this area was not considered in the Coastal Plains System and hence it is dealt with under the Sedimentary Zone of the Eastern Desert and Sinai Systems. The Ayun Musa Springs are located in an anticlinal zone, extending in a NNE - SSW direction, that is strongly affected by fault systems. The springs are situated along two parallel lines, extending along the fault lines that affect the Miocene water bearing sandy formation from which they issue. The water is at a temperature of 27°C and the total dissolved solids are 6000 ppm. During the 1960s 26 wells were drilled to a depth of around 600 metres, for coal prospecting. The drilling of these wells proved the occurrence of three principal hydrostratigraphical units: the Miocene sands, the Lower Cretaceous sandstone and the Jurassic sandy carbonate formations (Figure 10).

Ayun Musa Springs emerge from tension joints in the Miocene beds that lie unconformably on the Sinai Nubian Sandstone. It was observed that these springs are affected by tidal fluctuations that influence the artesian head as well as the discharges.

Helwan Springs: The area east of the Nile River, in the vicinity of Cairo, is characterized by the occurrence of a number of thermal springs. Most of these springs are flowing out of the fissured Eocene limestone which is widely distributed to the east of Cairo, and is affected by a complex pattern of faulting and jointing.

El Ramly (1969) reported that most of the springs originated as a result of earthquakes. He concluded that Helwan Spring came into existence after a strongly felt earthquake in June 1926.

The temperature of the Helwan Spring water is 32°C throughout the year, regardless of seasonal variation in air temperature. The genetic origin of the water was reported by Hemida (1976) to be an upward flow from the Nubian Sandstone aquifer which, being at a depth, accounts for the temperature.

Post Nubian Formations

In North Sinai the Middle - Upper Cretaceous limestones and dolomites as well as the Eocene limestones, being highly jointed and fractured, form hydrogeological units. Although these formations are largely untested, recent deep drilling programmes indicated that they are water bearing with water quality ranging between brackish and saline. Water temperatures from these wells are not yet available.

ADDENDUM

After the presentation of this paper it was possible to obtain more data relating to wells drilled in several places in Egypt. The data obtained are listed in Table 6. An isothermal gradient map has also been constructed (see Figure 11).

The map indicates that anomalies of temperature gradient almost coincide with the regional structural elements, such as the low anomalies (of 1°C/100 m) occurring at Abu Gharadic and

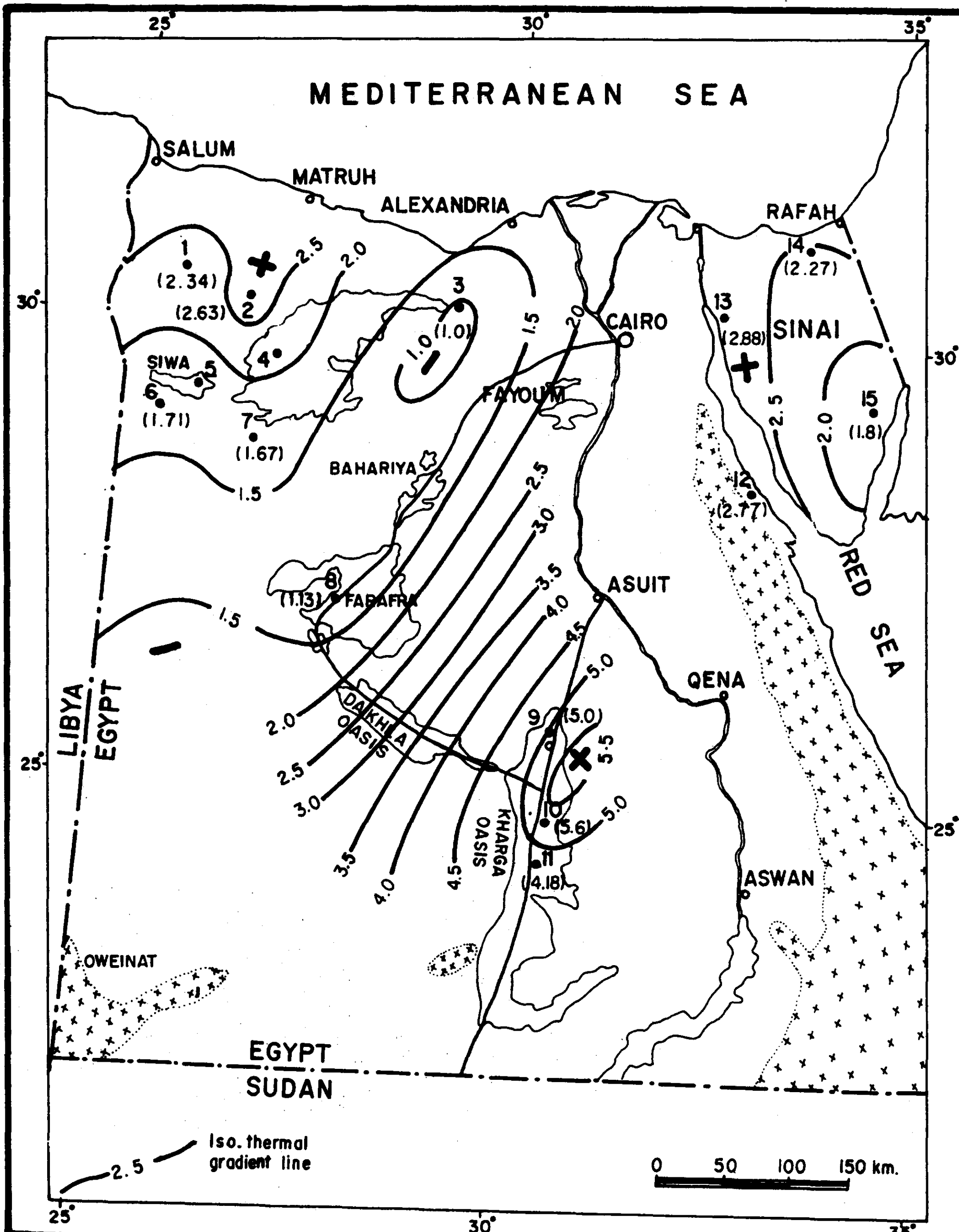

Figure 11: Isothermal gradient map.

Dessoky basins in the north Western Desert and the high anomaly along the Kharga Oasis anticline (5°C/100 m).

It has been recommended that the well thermal survey be completed for the remaining gaps in the southern part of the Western Desert, the Nile delta and Central Sinai, so that a better regional thermal outline can be achieved and consequently determine those areas of thermal energy potential.

Table 6: Additional data for wells drilled at several locations in Egypt.

Well Name	Depth (m)	Temperature (°C) Surface	BHT [(1)]	Thermal Gradient (°C / 100 m)
Western Desert :				
Fagur East	4197	33,30	131,60	2,34
Ghazalat North	3903	13,30	116,10	2,63
Fayed-1	3600	35,00	71,10	1,00
Kifar-1	2993	23,90	87,80	2,13
Zietun-1	3503	19,40	82,20	1,79
Siwa-1	3413	25,00	83,30	1,71
Bahrein-1	2993	29,40	79,40	1,67
Sheikh Marzouq	1150	25,00	38,00	1,13
Elmalaa-1	666	23,90	57,80	5,00
Garmashein-5	486	23,90	51,10	5,60
Baris-12	625	21,10	47,20	4,18
Eastern Desert :				
East Shagar	1704	28,90	76,10	2,77
Sinai :				
Ras Sudr-1	1350	32,20	71,10	2,88
Elmisri-1	3919	27,80	116,70	2,27
Shaira-1	804	22,00	36,50	1,80

BHT [(1)] = bottom hole temperature recorded at the indicated depth.

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THE HYDROGEOTHERMAL PROVINCES OF ISRAEL

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INTRODUCTION

The definitions of "thermal" and "mineral" water found in the literature are somewhat ambiguous and vary from country to country. Generally, all water with a total dissolved solids content exceeding 1000 mg/l are considered as "mineral", thus including brackish and saline water. Moreover, some national legislations have detailed specifications for the minimal concentrations of certain elements in water. This approach is based on balneologic criteria which allows classification of mineral water on the basis of the concentration of particular chemical constituents and on their therapeutic values (Eckstein, 1975).

"Thermal" waters are not better defined. Generally, they are classified as waters whose temperature is constant and appreciably above the local mean annual air temperature. In European countries, natural waters with temperatures higher than 20°C are classified as thermal. In the US, only those springs with temperatures at least 15°F above the mean annual local air temperature are classified as thermal (Eckstein, 1975). In Israel, the mean annual air temperature ranges between 20°C in the temperate highlands and 25°C in the arid Jordan - Dead Sea Rift Valley (Atlas of Israel, 1985). By adding the 15°F increment to these temperatures, the definition of thermomineral water suiting local conditions will be "... groundwater with a minimal TDS-concentration of 1000 mg/l and a constant temperature exceeding 25°C in the temperate highlands and 33°C in the Rift Valley ...". This classification covers all known springs and wells characterized by thermal anomalies as well as subaqueous hot springs outflowing in and along the coasts of the Dead Sea and Lake Tiberias.

Following this classification, three major hydrogeothermal provinces have been outlined in Israel:

The Sinai - Negev Nubian Sandstone province,
The Jordan - Dead Sea Rift Valley province,
The Hammat Gader province.

THE SINAI - NEGEV NUBIAN SANDSTONE PROVINCE

Hydrogeology

This province includes central Sinai in Egypt and most of the Negev in Israel. The province spreads fan-wise from the Gulf of Suez, around the northern and eastern margins of the igneous massif of Sinai and reaches to the Dead Sea and the Gulf of Elat, within the Rift Valley (Figure 1). The extent of this province coincides with the areal occurrence of the regional Lower Cretaceous Nubian Sandstone aquifer, locally known as the Kurnub Group. It comprises red, ferruginous, predominantly terrigenous sandstone and conglomeratic sandstone, arkose and sandy shales interbedded with marine carbonates and shales. In central and eastern Negev the thickness of this aquifer attains 350-400 m whereas in southern Negev it is 130-170 m. In northwestern Negev, the lithology of the Kurnub Group changes from clastic-continental to sedimentary-marine. The entire clastic sequence is unconformably and irregularly overlain by the Lower- to Upper Cretaceous impervious marine Hevion member which makes up part of the Judea Group, thus creating confined conditions in the underlying Nubian (Kurnub) aquifer. In the Negev this confined aquifer is buried within the depth range of 500-900 m (Rosenthal, 1986).

The Kurnub aquifer stands out by being an almost non-rechargeable reservoir of ancient (up to 30000 years old) water (Issar, *et.al.*, 1972; Galai, 1983). That period was characterized by a climate which was colder than at present. Due to the very low annual rainfall over the highly arid area (50-75 mm/yr) and extreme evaporation (> 2400 mm/yr), contemporary natural replenishment to this aquifer is almost negligible. It occurs on outcrops of the Kurnub Group surrounding the igneous massif of Sinai and exposed in erosional valleys and cirques ("makhteshim") of the Negev (Issar, 1979).

The immense body of paleowater (estimated at billions of cubic metres - Issar, *et al.*, 1972) flows from a piezometric level of +200 m in the Sinai highlands (well Nakhel Deep 1) in four main directions: to the central and northern Negev (+15 m), to the Dead Sea (−390 m), the Gulf of Elat and westward to the Gulf of Suez (Figure 1). The latter three areas are natural outlets of this regional aquifer.

In 1987/8, the total annual exploitation of Nubian paleowater reached 31 million m^3. Half of this volume is exploited close to the Dead Sea outlet creating there a deep cone of depression. The average yield of wells pumping from this aquifer is 250-300 m^3/hr, with a dynamic drawdown of approximately 30 m.

Hydrogeochemistry

Notwithstanding the great dimensions of the Nubian paleowater province, the chemical composition of its groundwater is astoundingly uniform and changes but slightly along the flow paths leading to the natural outlets.

Close to the ancient replenishment areas in Sinai, in well Nakhel Deep 1 (Figure 1; Table 1), the water stands out by its relatively low Cl-content (355 mg/l) and by its high SO_4-content (766 mg/l). Its ionic assemblage is clearly dominated by sulphate:

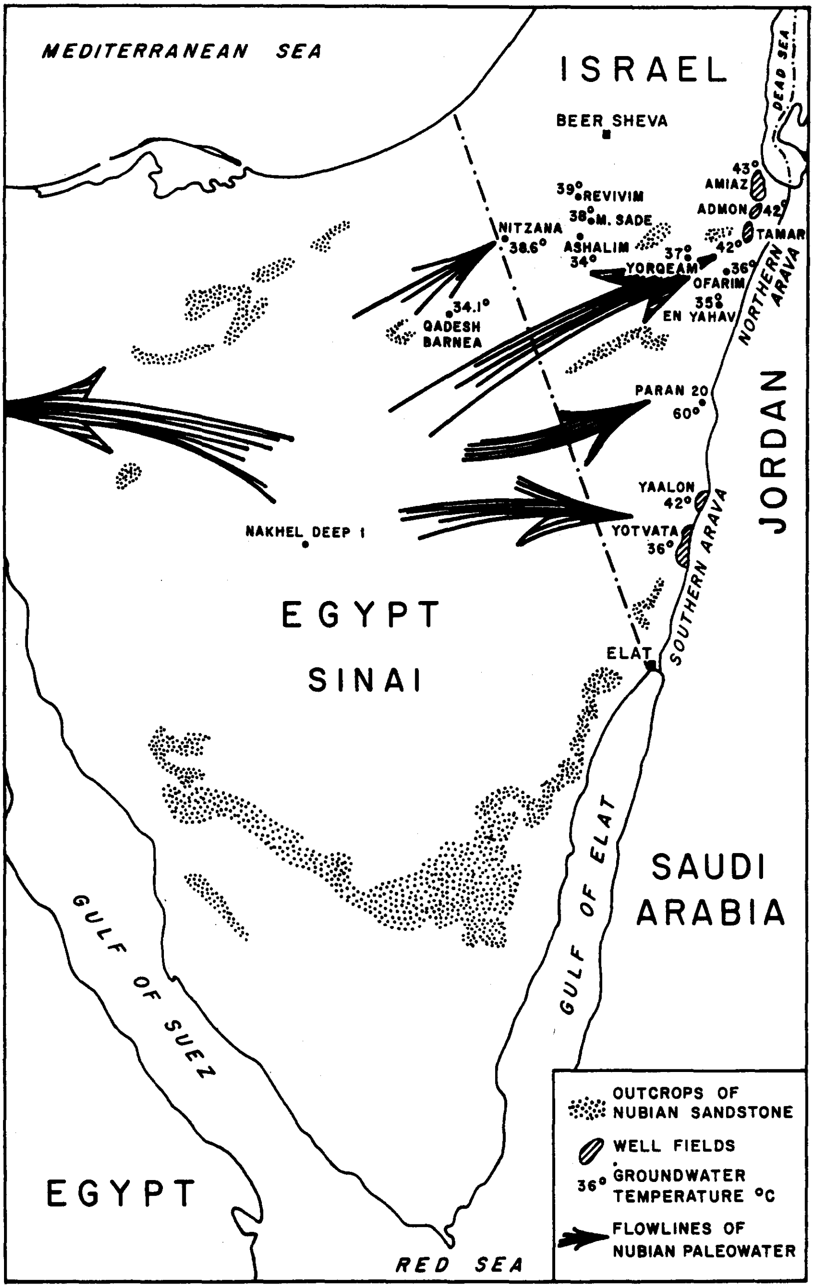

Figure 1: Location map, flow directions and groundwater temperatures in the Nubian Sandstone aquifer in Sinai and Israel.

Table 1: Average chemical composition and maximum temperatures of Nubian sandstone paleowater.

	Sinai		Sinai - Negev Boundary				Central Negev		Eastern Negev		Dead Sea area				Arava Valley			
	Nakhel Deep 1		Qades-Barnea		Nitzana 1		Ashalim 1		Yorgeam		Tamar		Amiaz		Northern Arava		Southern Arava	
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
TDS	1637	49,92	4003	129,4	4030	134,7	3658	119,4	2101	66,50	2498	76,20	7080	234,0	2030	64,12	1950	61,63
Cl	355,0	10,01	1464	41,28	1960	55,27	1578	44,50	701,0	19,77	683,0	19,20	2911	82,00	619,0	17,40	528,0	14,90
SO_4	576,0	11,99	882,7	18,36	520,0	10,83	440,0	9,10	400,0	5,20	716,0	14,90	1540	32,00	492,7	10,24	593,0	12,3
HCO_3	219,0	3,60	292,5	4,79	143,0	2,34	318,0	5,20	319,0	5,00	288,0	4,70	254,0	4,16	268,4	4,40	224,0	3,70
Ca	135,2	9,24	278,3	13,53	235,0	11,73	147,0	7,30	160,0	8,02	295,0	14,70	976,0	48,70	200,2	10,01	213,0	10,60
Mg	63,80	5,25	100,2	8,24	106,0	8,72	90,0	7,40	79,00	6,50	23,80	1,98	199,0	16,30	86,80	7,15	89,80	7,40
Na	214,0	9,31	930,0	40,46	1037	48,11	1019	44,30	414,0	18,01	452,6	19,70	1140	49,60	328,5	14,29	276,4	12.02
K	24,00	0,61	55,50	1,42	29,00	0,74	64,50	1,60	27,00	0,69	37,70	0,96	60,00	1,53	24,50	0,63	24,80	0,63

Table 1: Average chemical composition and maximum temperatures of Nubian sandstone paleowater (continued).

	Sinai	Sinai - Negev Boundary		Central Negev	Eastern Negev	Dead Sea area		Arava Valley	
	Nakhel Deep 1	Qades-Barnea	Nitzana 1	Ashalim 1	Yorgeam	Tamar	Amiaz	Northern Arava	Southern Arava
Ionic sequence (meq/l)	(Na+K)> Ca>Mg SO_4>Cl> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3	(Na+K)> Mg>Ca Cl>SO_4> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3	(Na+K)> Ca>Mg Cl>SO_4> HCO_3
$rHCO_3/rCl$	0,36	0,11	0,04	0,11	0,26	0,24	0,05	0,24	0,24
$rSO_4/rHCO_3$	3,33	3,82	4,62	1,75	1,58	3,15	7,68	2,40	3,36
rSO_4/rCl	1,20	0,44	0,20	0,20	0,42	0,77	0,39	0,58	0,86
rMg/rCa	0,57	0,59	0,74	1,00	0,81	0,13	0,33	0,72	0,69
rNa/rCl	0,93	0,98	0,82	0,99	0,91	1,02	0,60	0,81	0,82
rNa/rK	15,16	28,50	60,82	26,80	26,06	20,36	32,28	22,85	18,85
Cl/Br	--	--	--	350,0	326,0	387,0	80,23	272,0	319,0
rQ	0,42	0,58	0,89	0,51	0,59	0,75	1,34	0,67	0,66
No. of samples	3	5	2	2	3	44	32	15	3
Max. Temp. (°C)	--	34,1	38,6	34,0	37,0	42,0	43,0	42,0	42,0
pH	--	--	6,90	7,05	6,90	6,95	6,85	7,05	6,90
CO_2 free	--	--	73,00	158,0	--	--	--	--	--
H_2S	--	--	--	--	--	--	--	--	--
^2H	--	--	--	--	−35,70	−50,00	−42,00	--	−50,15
^3H	--	--	--	--	0,70	--	--	--	<1
^{18}O	--	--	--	--	−6,71	−7,12	−6,20	−7,38	−7,68
^{14}C	--	--	--	--	6,95	4,70	--	--	6,00

$rSO_4 > rCl > rHCO_3 \qquad r(Na+K) > rCa > rMg$

The water is characterized by such ionic-ratios as:

$rSO_4 / rCl = 1,2; \qquad rSO_4 / rHCO_3 = 3,33; \qquad rNa / rCl = 0,93$

The relatively high value of the rNa / rCl ratio may be attributed to the high percentage of igneous silicate components in the arkose.

As previously mentioned, the flow of this paleowater body fans out in four main directions towards the natural outlets of this huge groundwater basin (Figure 1):

- to the southern Arava (Jordan Rift Valley) and the Red Sea,
- to the northern Arava and the Dead Sea,
- to northeastern Negev and the Dead Sea,
- to central and northwestern Negev.

Along the first three flow paths the chemistry of paleowater changes but slightly. In all cases, the paleowater is characterized by chlorides in the 520-700 mg/l range and by a chloride-dominated ionic assemblage:

$rCl > rSO_4 > rHCO_3 \qquad r(Na + K) > rCa > rMg$

The typical hydrochemical characteristics are given in Table 1. All waters are characterized by an average Fe^{+2}-content of 1,7 ppm, though concentrations as high as 16,7 ppm were reported by Eckstein (1975). This water has also a Mn-content of 70 ± 0.5 ppb, which is one order of magnitude higher than in fresh water exploited from calcareous aquifers (Arad, *et al.*, 1984). The waters stand out by their high H_2S content (1-4 mg/l). The stable isotopes are very depleted and the waters are very old: $^{18}O = (-7)\text{-}(-8)$; $^{2}H = (-55)\text{-}(-64)$; T < 1 TU.

The waters flowing to the central and northern Negev stand out by their much higher chloride values which are in the 1450-2000 mg/l range. The ionic ratios and all other hydrochemical features resemble those characterizing the other three flow paths described previously. These high salinities may be the result of major changes in aquifer lithology. In this part of the country, within the Nubian Group sequence, sand and sandstone are no longer the dominant lithological component of the aquifer but are gradually replaced by carbonates and shales. This seems to have a direct bearing on groundwater flow rates and hence on the duration and intensity of rock-water interaction. On the other hand, the deep-seated reverse faults recently discovered in the area (Weinberger, *et al.*, 1989) may act as conduits for upflowing brines (Ilani, *et al.*, 1988). Indications supporting such a salinization mechanism were detected by the author in the chemical composition of water from well Nitzana 1.

Close to the natural outlet of this aquifer near the Dead Sea, at the margins of the Rift Valley, the salinity of the Nubian paleowater increases sharply and the chemical composition changes radically. These changes are mainly due to Ca-chloride brines upflowing along the Rift faults. The chemistry of these brine-affected paleowaters is given in Table 1. The main hydrochemical features characterizing these waters are:

- increase of the Cl-content to over 4500 mg/l,
- the ionic assemblage changes to

  $rCl > rSO_4 > rHCO_3 \qquad rCa > rMg > r(Na + K)$

- the main changes in ionic ratios are the sharp drops in the rNa / rCl and rMg / rCa ratios to 0,57 and 0,33 respectively,
- the Cl / Br ratio drops from 275 to 65,
- the $rQ = rCa / r(SO_4 + rHCO_3)$ increases as high as 3,98.

All these changes are typical of the inflow of deep-seated Ca-chloride brines (Rosenthal, 1988b).

Similar changes in the composition of Nubian paleowater were observed southward, also along the western margins of the Rift, near the dome of Timna (Rosenthal, *et al.*, 1989).

Geothermics

All over the Negev, groundwaters related to the contemporary replenishment cycle are characterized by temperatures in the 20-23°C range. The temperatures of Nubian paleowater are in the 34-44°C range, with one exception of 59°C in well Paran 20 located in the Rift Valley (Figure 1). Eckstein & Rosenthal (1968) and Eckstein (1974, 1975) pointed out that the relatively high temperatures of this paleowater are conditioned by the normal regional geothermal gradient. A recent survey (Rosenthal, 1988) showed that in the central Negev the temperatures are directly related to the absolute elevations (vs MSL) of a major, impervious rock formation overlying the Kurnub (Nubian sandstone) and Judea Groups, thus creating confined conditions. The average temperature of Nubian paleowater as measured along the western margins of the Rift, is explained in a similar manner and can be easily reconstructed in the following way:

- the average temperature of groundwater related to the contemporary active hydrological cycle is in central Negev (+100 m above MSL) 20°C,
- ground elevation along the western margins of the Rift is –300 m (below MSL), i.e. 400 m lower than in the Negev highlands,
- the normal average geothermal gradient would thus raise water temperature to 32-33°C,
- as paleowaters are pumped (along the borders of the Rift) from depths of at least 300 m below ground surface (i.e. –600 m below MSL) and, in all cases from beneath the regional confining layer, the average temperature of water of 42°C is easily obtained. The same holds true for the "exceptional" borehole Paran 20 in which the water temperature is 59°C. This is the deepest (1564 m) water-producing well in the country, in which the top of the Nubian sandstone is at –1300 m below MSL.

In the central and northern Negev, relatively elevated temperatures (in the 33-38°C range) were measured in the Upper Cretaceous Judea Group which comprises mainly karstic carbonates. Such temperatures are uncommon for the Judea Group aquifer and always coincide with the occurrence of brackish water characterized by a chloride value of 1200-2900 mg/l. For all cases, it was proven (Rosenthal, *et al.*, 1988) that these high temperatures and exceptional salinities were measured in areas in which Nubian paleowater penetrated into the overlying Judea Group. This may have been caused by upward leakage conditioned by the following factors:

- it could occur in areas in which the impervious layer separating the Kurnub and Judea Groups was not deposited due to local facies changes,
- buried, deep-seated faults create suitable geological conditions facilitating lateral flow from the Nubian (Kurnub) aquifer into karstic units of the Judea Group sequence. The mixing of thermal Nubian paleowater with the much colder water flowing in the Judea Group karstic horizons produces the cooling effect, lowering water temperatures to 33-38°C. The relatively high salinities observed in the wells of central Negev seem to be directly related to the higher concentration of Nubian water flowing from central Sinai to central Negev. Mixing lines drawn between Nubian and Judea Group hydrochemical end-members fully support this model.

State of utilization

At the present time, 37 wells exploit Nubian paleowaters. The average depth of such wells is 600 m and their yield is in the order of 300-500 m^3/hr. These wells are usually equipped with stainless steel casings and fine-mesh Johnson-type screens specially adapted to the particular sand grainsize. The special casing is required because of the high corrosivity of the water.

During the last five hydrological years, the average annual extraction of Nubian paleowater was 40 million m^3/yr. Most of this water (35 MCM) is exploited in the Dead Sea area and in the Arava, both areas being part of the Rift Valley. Five MCM are pumped in the central Negev.

Almost all water pumped in the Dead Sea area is used for industrial purposes. In this area only 0,3 MCM are used annually for balneological purposes in spas located along the shores of the Dead Sea.

Most of the water extracted in the Arava and in central Negev is used for the irrigation of highly profitable vegetables that are exported. Obviously, the thermal potential of this water is not exploited and is actually lost. However, during the last five years, approximately 1 MCM are used annually to heat, for 1000 winter-hours, large-surface hot houses in the desert in which are cultivated melons, water melons and tomatoes. These hot houses are specially adapted low, tunnel-like structures built of thick, polyethylene sheets spread over metal framing. Nubian thermal water circulates through a system of plastic sleeves laid on the ground and among the plant beds. The circulation of thermal water heats the soil and the inner atmosphere of the tunnel creates interior temperatures completely different from those outside. Nubian paleowaters of the highest available temperatures (42-44°C), and including those of well Paran 20 (59°C), are used. After cooling, the water is used for irrigation of cultivations grown either under the tunnels or outside, in nearby fields. At present, 44 hectares of such tunnels are successfully exploited in the Negev and all agricultural products thus produced are exported. By 1990 the area covered by such tunnels will be 95 hectares. The annual value of energy saved by this heating method is US$ 1,240,000.

THE JORDAN - DEAD SEA RIFT VALLEY PROVINCE

This province forms part of the Syrian - Red Sea - East African Rift Valley system. The groundwaters of this vast province are thermal, radioactive and sulphurous. The dominant hydrochemical feature of groundwater in this province is the occurrence of Mg- and Ca-chloride brines mixing with fresh groundwater draining from replenishment areas adjacent to the Rift. In view of geological considerations, this province is subdivided into three regions which are described separately. The common hydrogeothermal model will be discussed in the concluding remarks.

The Dead Sea basin

Hydrogeology: In the entire Israeli part of the Rift, the Dead Sea basin trends north-southward and is limited on both sides by fault block escarpments. The stratigraphical sequence and the geological structure of the area have been examined in detail by various authors and reviewed by Bentor & Vroman (1960). The step-faulted blocks forming the western escarpments are built mainly of limestone and dolomite formations interbedded with clay and marl of Cenomanian - Turonian age, all related to the Judea Group sequence. They are overlain by chalk beds with interlayers of flint and phosphorite of Senonian age. Bituminous shales representing the Maestrichtian - Paleocene period are present as relicts on the top of downfaulted step-blocks. All these formations are related to the Mt. Scopus Group. Rift Valley sediments are exposed around the Dead Sea itself and cover unconformably the lower tectonic blocks. These sediments are evaporites of the Oligo - Miocene Sdom formation, clastic psamitic and pelitic red beds of the Neogene Hazeva formation, lacustrine marls interfingering with clastics of the Plio - Pleistocene Samra and Lisan formations and with Recent fluviatiles (Bentor & Vroman, 1960).

Being a low depression and having deeply and densely faulted margins, the Dead Sea area is a regional drainage basin and a mixing zone for groundwater flowing to it from adjacent mountain areas.

The main groundwater bodies flowing to the Dead Sea depression are:

- Nubian Sandstone paleowater (characterized and discussed in the previous section),
- fresh water derived from flash floods occurring in the mountains east and west of the Dead Sea depression (Yehieli, *et al.*, 1959),
- thermal brines ascending from the subsurface of the Rift,
- contemporary Dead Sea water also plays a role (though of minor importance) in the hydrochemistry of groundwater occurring in the region as it is an interface contact with the previously mentioned groundwater bodies.

The chemical composition and the thermal character of springs emerging along the western shores of the Dead Sea are closely related to the different contributions from, and to mixing relations between, the four above mentioned water bodies.

North of the Mount Sdom diapir, all along the western shore of the Dead Sea numerous thermo-mineral springs emerge. The most prominent are Hammei (i.e. hot spring of) Zohar, Hammei

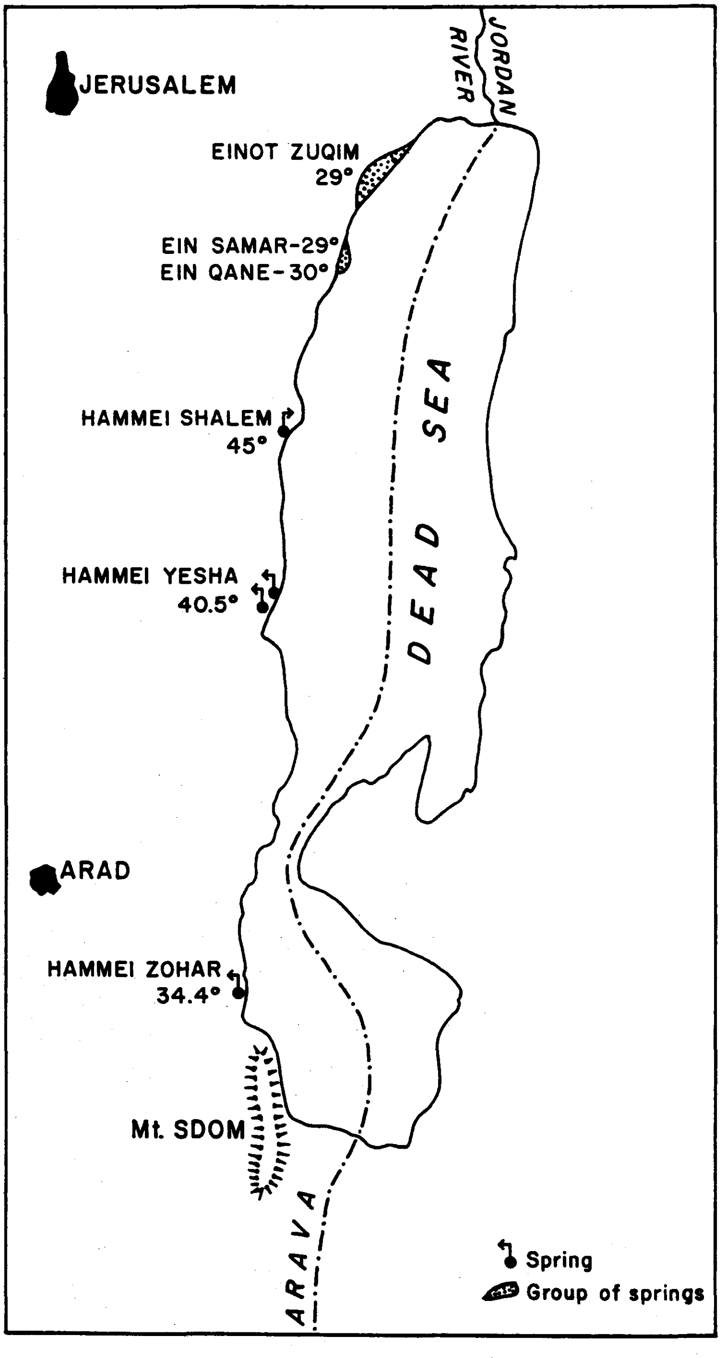

Figure 2: Location map and maximum groundwater temperatures in the Dead Sea area.

Table 2: Average chemical composition and maximum temperatures of thermomineral springs in the Dead Sea area.

	Hammei Zohar (mg/l)	Hammei Zohar (meq/l)	Hammei Shalem (mg/l)	Hammei Shalem (meq/l)	Hammei Yesha (mg/l)	Hammei Yesha (meq/l)	Einot Zuqim (mg/l)	Einot Zuqim (meq/l)	Ein Qane (mg/l)	Ein Qane (meq/l)	Ein Samar (mg/l)	Ein Samar (meq/l)	Dead Sea Water (mg/l)	Dead Sea Water (meq/l)
TDS	206353	7931	191838	7306	179032	6753	4856	170,7	--	--	--	--	330421	12768
Cl	139500	3986	127036	3629	117530	3358	2766	76,50	3913	111,8	779,0	22,20	221950	6341
SO_4	830,0	17,30	829,6	17,20	1060	22,10	68,00	1,40	49,50	1,00	33,00	0,70	711,0	14,80
HCO_3	183,0	3,00	137,0	2,20	142,0	2,30	354,0	5,80	268,0	4,40	280,0	4,60	--	--
Ca	14000	700,0	12080	604,0	10300	515,0	328,0	16,40	340,0	17,00	112,0	5,60	16080	804,0
Mg	26000	2167	21888	1824	18700	1558	360,0	30,00	740,0	61,60	158,0	13,10	44540	3711
Na	22200	965,2	26015	1131	27800	1209	741,0	32,20	835,0	36,30	185,0	8,00	38600	1678
K	3640	93,30	2853	98,80	3500	89,70	328,0	8,40	139,0	3,60	27,80	0,70	8540	219,0
Ionic sequence (meq/l)	$Cl>>SO_4>HCO_3$ $Mg>>(Na+K)>Ca$		$Cl>>SO_4>HCO_3$ $Mg>(Na+K)>Ca$		$Cl>>SO_4>HCO_3$ $Mg>(Na+K)>Ca$		$Cl>>SO_4>HCO_3$ $Mg>(Na+K)>Ca$		$Cl>SO_4>HCO_3$ $Mg>(Na+K)>Ca$		$Cl>SO_4>HCO_3$ $Mg>(Na+K)>Ca$		$Cl>>SO_4$ $Mg>(Na+K)>Ca$	
$rHCO_3/rCl$		0,0007		0,0006		0,0007		0,07		0,04		0,20		--
$rSO_4/rHCO_3$		5,76		7,67		9,52		0,24		0,23		0,14		--
rSO_4/rCl		0,004		0,004		0,006		0,02		0,009		0,03		0,002
rMg/rCa		3,09		3,01		3,02		4,01		3,62		2,31		4,61
rNa/rCl		0,24		0,31		0,36		0,33		0,32		0,36		0,26
rNa/rK		10,34		11,44		13,47		11,34		10,19		11.32		7,66
Cl/Br		41,50		42,30		53,27		48,50		47,70		62,30		40,70
rQ		34,45		31,13		21,15		17,97		3,13		1,06		54,30
No. of samples		27		3		19		25		7		4		numerous
Max. temp. (°C)		34,4		45,5		40,5		29,0		30,0		29,0		--
pH		6,10		6,36		6,40		6,40		--		--		--
CO_2 free		421,0		400,0		203,0		--		--		--		--
H_2S		16,00		28,00		33,00		7,00		--		--		2,00
^2H		–36,00		–38,00		–35,70		--		--		--		--
^3H		--		--		--		--		--		--		--
^{18}O		–4,50		–4,70		–4,00		--		--		--		--
^{14}C		10,18		10,31		--		--		--		--		--
^{13}C		–0,86		--		--		--		--		--		--

Shalem, Hammei Yesha, Einot (i.e. springs of) Qane, Samar and Zuqim (Figure 2). All these springs emerge close to the Dead Sea waterline, at the foot of the high fault escarpment of carbonate formations related to the Judea Group (Eckstein, 1975). The chemical composition and elevated temperatures of these springs are mainly influenced by ascending brines which are differentially diluted by various amounts of fresh or brackish water deriving from other aquifers.

Hydrogeochemistry and geothermics: The chemical composition of water from representative sources emerging along the fault escarpment bordering the Dead Sea to the west is given in Table 2. It is evident that all these waters relate to one, well-defined hydrochemical group: the Zohar - Yesha Group (Mazor, *et al.*, 1969).

The average salinity of the three main representatives of this group (Zohar, Yesha and Shalem springs) is 128 000 mg/l chloride. Their ionic assemblage is:

$rCl >>> rSO_4 > rHCO_3 \qquad rMg >> r(Na + K) > rCa$

At first sight, the ionic assemblage and the ratios resemble those of contemporary Dead Sea water. However, the examined water stands out by its gas content, radioactivity and elevated temperatures, viz: H_2S, 16-33 ppm; CO_2, 203-421 ppm; radium, up to 32 pC/l; radon, up to 21000 pC/l; T°C, 34-45.

The waters of Einot Zuqim, Qane and Samar, also related to this group, are heavily diluted and cooled by fresh water draining from the Judea Mountains.

Mazor, *et al.*, (1969) suggested that the water of this hydrochemical group is a mixture of recycled Dead Sea water with groundwater which could be related to the Nubian Sandstone aquifer.

Starinsky (1974) assumed that these brines represent a residual product of evaporated Pliocene sea water which was trapped in the primordial Sdom depression within the Rift. During the course of its evolution, this evaporating brine precipitated halite. Starinsky suggested that this brine was the main source of the contemporary Dead Sea water.

Considering the low regional thermal gradient (1°C per 57-150 m; Eckstein & Rosenthal, 1968), it appears that these brines do not originate at depths greater than 300-500 m below surface. The mechanism of their upflow has not, so far, been elucidated.

State of utilization: At present, the water emerging from the previously mentioned sources is also used for balneological purposes in spas, in parallel with water derived from the Nubian Sandstone aquifer. Exploitation is by wells equipped with special non-corrosive casing. A total of 60 m^3/day are nowadays pumped. The annual rate of exploitation does not exceed 0,2 MCM. Plans for further balneological development are now being formulated. They depend mostly on the future developments of the Dead Sea Works Ltd., which have long-term concessions on the whole area along the shores of the Dead Sea.

The Lake Tiberias basin

The geology and hydrogeology of this part of the Rift Valley were studied in great detail by Golani (1962), Saltzman (1964), Mazor & Mero (1969), Goldschmidt, *et al.*, (1967), Starinsky (1974) and Rosenthal (1988). The mountainous area of eastern Lower Galilee slopes down to the Tiberias basin in a series of step faulted blocks, built of calcareous rock formations (of Cenomanian to Eocene age) covered by Neogene fluviatile sediments and multiple Neogene to Pliocene basalt flows. The Golan Heights in the east are built essentially of a similar section, with Eocene outcrops at the base, Pleistocene basalts at the top and Neogene sediments in between.

A host of warm and hot mineral springs is scattered along the shores of Lake Tiberias and on its floor. It seems that their occurrence is tectonically controlled as in other parts of the Rift.

The most important springs are those emerging along the western shores of the Lake (coinciding with the western fault of the Rift). They are clustered in three main groups: Hammei Tveria (the Tiberias hot springs), Einot (the springs of) Fuliya and Einot Sheva (Figure 3). They all issue from more or less isolated and elevated tilted blocks covered by Neogene sedimentary and volcanic formations. Along the eastern coast, to the north of Ein Gev, a host of sulphurous thermal springs emerge close to the water line. Such water was also discovered in a series of exploration wells drilled along the eastern shore of the lake.

Because of the great variability of salinities and temperatures observed in the numerous groundwater sources in the area, it is difficult to detect, at first sight, common hydrogeochemical features. Closer study reveals that all these waters are different mixing products between artesian, thermal, radon-rich Ca-chloride brines, fresh groundwater currently replenished by the active hydrological cycle and fresh lake water. Differences in salinity and thermicity of the sources are due to local structural conditions controlling the mixing between ascending brines and the fresh components. Though the temperatures of some groundwater sources are less than 33°C (the threshold temperature of fresh water in the Rift), these sources have to be considered as a part of the hydrogeological system. The hydrogeochemical model elucidating the relations between the various hydrochemical groups will be discussed in the concluding remarks.

Hydrogeology: According to Golani (1962) and Saltzman (1964), each group of springs emerges at intersections of two systems of faults (striking NESW-NWSE and forming rhomb-shaped patterns), adjacent to faulted and tilted blocks.

Hammei Tveria (Tiberias hot springs) (Figure 3): These springs stand out by their high salinities (up to 17800 mg/l Cl) and elevated temperatures (59-62°C) (Table 3). The three main springs forming this group emerge close to a major fault of the Rift system and the tilted block of Mt. Herodes. The total outflow of these springs is 100 m^3/h. At a distance of 100 m offshore and to the east of these springs, a host of submarine springs of similar salinities and temperatures emerge. These submarine springs (and many others emerging on the bottom of the lake) raise the salinity of the lake which is the regulating reservoir of the National Water System. Therefore, since the early 1960s, 90% of this water is diverted by a network of pumping wells into a special diversion conduit; only 10% of the water is exploited for balneological purposes.

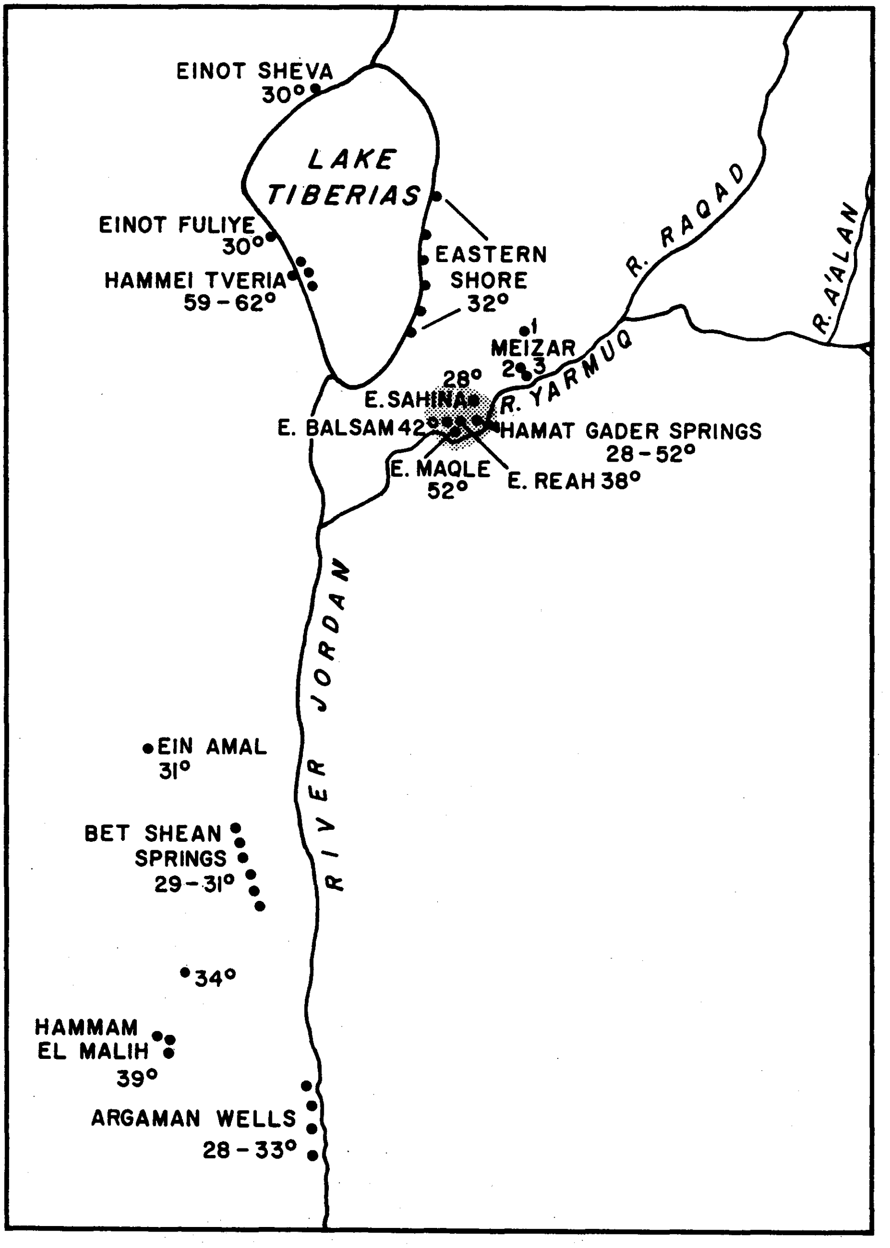

Figure 3: Location map and maximum groundwater temperatures in the Lake Tiberias area, in the Jordan Valley and in the Hammat Gader area.

Table 3: Average chemical composition and maximum temperatures in sources around Lake Tiberias.

	Tiberias Hot Springs						Fuliye		Sheva		Eastern Shore	
	Main spring		Roman spring		New spring		Fuliye - Magdala spring no. 11		Ein Nur		Ein Gev borehole no. 1071	
	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)
TDS	273189	977,5	29711	1047	29455	1044	2385	79,44	4663	159,9	34916	1256
Cl	16675	476,4	17715	506,1	17223	492,1	1108	31,65	2427	69,30	21971	619,0
SO_4	744,1	15,50	770,2	16,00	755,4	15,70	141,6	2,95	202,6	4,20	35,00	0,70
HCO_3	157,1	2,60	150,8	2,50	145,1	2,40	313,2	5,13	309,1	5,10	384,0	6,30
Ca	3142	157,1	3467	173,3	3552	177,6	191,4	9,60	413,7	20,70	1476	74,00
Mg	569,4	47,40	614,7	51,20	618,2	51,50	80,40	6,70	115,2	9,60	2100	173,0
Na	6208	269,9	6622	287,9	6806	295,9	528,5	22,90	1147	49,80	8633	375,0
K	335,7	8,60	372,4	9,60	355,3	9,10	21,90	0,56	48,20	1,20	317,0	8,10
Ionic sequence (meq/l)	$Cl>SO_4>HCO_3$ (Na+K)>Ca>Mg		$Cl>SO_4>HCO_3$ (Na+K)>Ca>Mg		$Cl>SO_4>HCO_3$ (Na+K)>Ca>Mg		$Cl>HCO_3>SO_4$ (Na+K)>Ca>Mg		$Cl>HCO_3>SO_4$ (Na+K)>Ca>Mg		$Cl>HCO_3>SO_4$ (Na+K)>Mg>Ca	
$rHCO_3/rCl$		0,005		0,0049		0,004		0,16		0,07		0,01
$rSO_4/rHCO_3$		5,96		6,41		6,54		0,57		0,84		0,111
rSO_4/rCl		0,03		0,031		0,03		0,09		0,06		0,001
rMg/rCa		0,30		0,29		0,28		0,70		0,46		2,33
rNa/rCl		0,56		0,56		0,60		0,72		0,71		0,61
rNa/rK		31,30		30,14		32,48		41,00		40,50		46,30
Cl/Br		78,70		77,00		70,70		149,7		115,0		82,30
rQ		8,70		9,40		9,80		1,18		2,22		10,57
No. of samples		30		27		24		29		17		7
Max. temp. (°C)		62,0		59,0		62,0		30,0		30,0		32,0
pH		6,50		6,60		6,50		6,50		6,60		--
CO_2 free		115		136		--		--		--		--
H_2S		1,40		1,90		--		--		--		<10
^{2}H		−18		−20		−12		−22		−28		−13
^{18}O		−3,9		−3,3		−3,4		−5,2		−5,9		−1,7
^{13}C		5		--		--		--		--		--
^{222}Rn	5600 ± 325			--	3600 ± 700		6300 ± 700		4000 ± 800			--
^{226}Ra	128 ± 13			--	138 ± 16		0		8,50 ± 0,20			--

Einot Fuliye: This is a group of 11 springs emerging on the surface and underwater around a faulted and tilted limestone block located near the biblical site of Magdala. The total outflow of these springs approaches 1000 m^3/h at an average temperature of 30°C and Cl-content of 900 mg/l. Here, again, a great part of the natural outflow is diverted to preclude salinization of lake water.

Einot Sheva: This group includes the springs of Nur, Sheva and Dar emerging at the northwestern extremity of the lake, at close proximity to a calcareous fault block.

The highest salinities (2426 mg/l Cl) were observed in the water of Ein Nur (30°C). This spring is characterized by the highest yield in the area (up to 3200 m^3/h).

The Ein Gev Group (eastern shore of the lake): This is a host of seepages along the eastern shore of the lake, close to the water line, emerging from alluvium covering buried faults and tilted structures. These are sulphurous springs (5-10 ppm H_2S), the chloride content of which does not exceed 1000 mg/l. The temperatures are in the 29-32°C range. Obviously, these seepages are dilution products of saline (> 21000 mg/l Cl) end members (discovered in exploration boreholes drilled along the shore) and fresh lake water.

Hydrogeochemistry and geothermics: The chemical composition and maximum temperatures of representative sources emerging along the western and eastern shores of the lake are given in Table 3. The groundwaters found along the western shore of the lake stand out because of their specific chemical composition, their high temperatures and radioactivity, which differ from those observed along the eastern shore. Geochemical investigations (Mazor, *et al.*, 1969; Goldschmidt, *et al.*, 1967; Starinsky, 1974; Rosenthal, 1988) showed that these are different dilution products of an evaporated Ca-chloride brine end-member. This is indicated by the following ionic-ratios:

rQ >> 1	(8,7 - 9,8)
rNa / rCl < 0,86	(0,56 - 0,30)
rMg / rCa < 0,70	(0,28 - 0,35)
Cl / Br << 286	(70 - 79)

The waters of the Fuliye and Sheva springs do not differ geochemically from those of Tiberias Hot Springs. The only difference is the degree of their dilution by fresh lake water and by groundwater deriving from contemporary recharge to basalt and limestone aquifers draining to the lake.

The saline end-member discovered in exploration wells along the eastern shore is also related to Ca-chloride brines. However, it differs because of the high rMg / rCa ratio (2,33), which defines it as a separate hydrochemical entity.

Considering hydrochemical and isotopic data, Mazor, *et al.*, (1969) and Gat, *et al.*, (1969) suggested that Hammei Tveria and the sources along the eastern shores of the lake are two nucleii of "fossil water mixtures almost undiluted by contemporary groundwater. Other thermomineral waters (Fuliye, Sheva) show the effect of present day dilution by both lake and aquifer water ...".

Groundwater with a chemical composition similar to that of water emerging from Hammei Tveria was encountered in the Rosh Pina wildcat well located in the Rift, a few kilometres to the north of the lake. This water was detected in Lower Jurassic beds, at a depth of 2500 m where the temperature was 70°C. In view of that, Starinsky (1974) deduced that the water of Hammei Tveria (60-62°C) rises from a depth of 2000 m. This supports the conclusion reached by Mazor & Mero (1969), according to which the elevated groundwater temperatures were not caused by thermal anomalies but by rapid upflow of water from depths greater than 600 m.

State of utilization: The thermomineral water of Hammei Tveria is utilized for balneological purposes. This is the main balneotherapeutic centre for the country.

The Jordan Valley (Figure 3)

The geology and hydrology of the region were studied by numerous geologists (Shulman, 1959; Rofe & Raffety, 1965; Rosenthal, 1972, 1988; Bender, 1968; Burdon, 1959; Flexer, 1961; Picard, 1932, 1934, 1955). Hot springs (32-39°C) in this part of the Rift are associated mostly with secondary faults branching out, in the form of a crescent, north-westward from the major rift structures. The salinity of the water (900-2000 mg/l) is due to a Ca-chloride end-member. However, the waters are rather fresh and cool due to the higher rate of dilution with fresh and cold components from shallow aquifers. The most important spring is Hammam el Malih (39°C), which is probably fed by deep Jurassic aquifers. Rosenthal (1988) showed that all saline and thermal waters in this area are again mixtures between a Ca-chloride source brine with fresh and cool water of the active hydrological cycle.

Origin of the Jordan Valley brines

While investigating the saline groundwater of the Jordan Valley, Rosenthal (1988) identified two hydrochemical types of Ca-chloride groundwater:

- The Neve Ur type characterized by rMg / rCa > 1 and
- The Devora type with rMg / rCa < 1.

The occurrence of Ca-chloride brines was established according to Sulin (1935, 1946).

In all cases the phreatic Neve Ur waters overlie the confined Devora-type water body. The latter are thermal and of much higher salinity, which increases with depth.

The Neve Ur type (rMg / rCa > 1; rQ > 1): The end-member of this hydrochemical type was identified in well Neve Ur T/1 located in the center of the Jordan Valley. While drilling through Quaternary clastics, the well struck high salinity groundwater (22050 mg/l Cl) at a piezometric head (259,4 m below MSL), slightly lower than the regional level of fresh groundwater (−256,8 m). The hydrochemical characteristics of the end-member are as follows:

$rCl > rSO_4 > rHCO_3$ $rNa > rMg > rCa$
$rMg / rCa = 2,08$ $rNa / rK = 126$
$rNa / rCl = 0,63$ $rQ = 3,84$

Similar Mg-rich Ca-chloride groundwaters from sources located along the eastern and southern shores of Lake Tiberias (of similar salinities and chemical characteristics) are there characterized by Cl / Br ratios in the 80-150 range (Starinsky, 1974).

The Devora type (rMg / rCa < 1; rQ > 1): Such groundwaters were identified in various groundwater sources in the Jordan Valley. The end-member of the Devora type was identified in drill-stem tests of the Devora 2A, Rosh Pina 1 and Sarid 1 wildcat wells drilled in adjoining areas (Figure 4).

The Devora type waters are confined, with much higher salinities and temperatures than those of Neve Ur waters and originate from deeper stratigraphic levels (Lower Jurassic and older). Their chemical characteristics are as follows:

$rCa > rHCO_3 > rSO_4$ $rCa > rNa > rMg$
$rMg / rCa = 0,1$ $rQ = 186$
$rNa / rCl = 0,47$ $Cl / Br = 57$
$rNa / rK = 37\text{-}49$ $pH = 4,7\text{-}4,9$

The piezometric heads of these brines were calculated from pressure-release tests and were found to be always in the 40-105 m below MSL range; i.e., usually exceeding ground surface elevations.

According to Rosenthal (1988) and Ilani, *et al.*, (1988), the Devora-type brines were formed in the southern part of the country as a result of sea water evaporation that occurred during the Cambrian - Lower Cretaceous continental time span. Due to subsequent structural events, the initial Mg-rich brines migrated northward under confined conditions and increasing contact with carbonate rocks. These inferred flow conditions could provide a suitable environment for the chemical diagenesis of brine, i.e. the gradual exchange of Mg with Ca-ions originating in the marine limestones interfingering and replacing north and northeastward the continental formations.

The high pressures characterizing these brines could be related to their confinement under a 3 km thick column of sediments. The lithostatic pressures thus exerted on the brines were certainly augmented by Late Cretaceous to Late Tertiary orogenic folding (Freund, *et al.*, 1975) and by plate and block movements.

The Jordan - Dead Sea Rift Valley with its fault-conditioned structures is an ideal area for the present day manifestation of these brines. Due to the deep and dense faulting along the margins of the Rift, hydrological contact was established with the deep-seated formations storing the brines, thus facilitating their upflow and intermixing with water from other aquifers. This would explain the high incidence of these brines relative to other parts of the country.

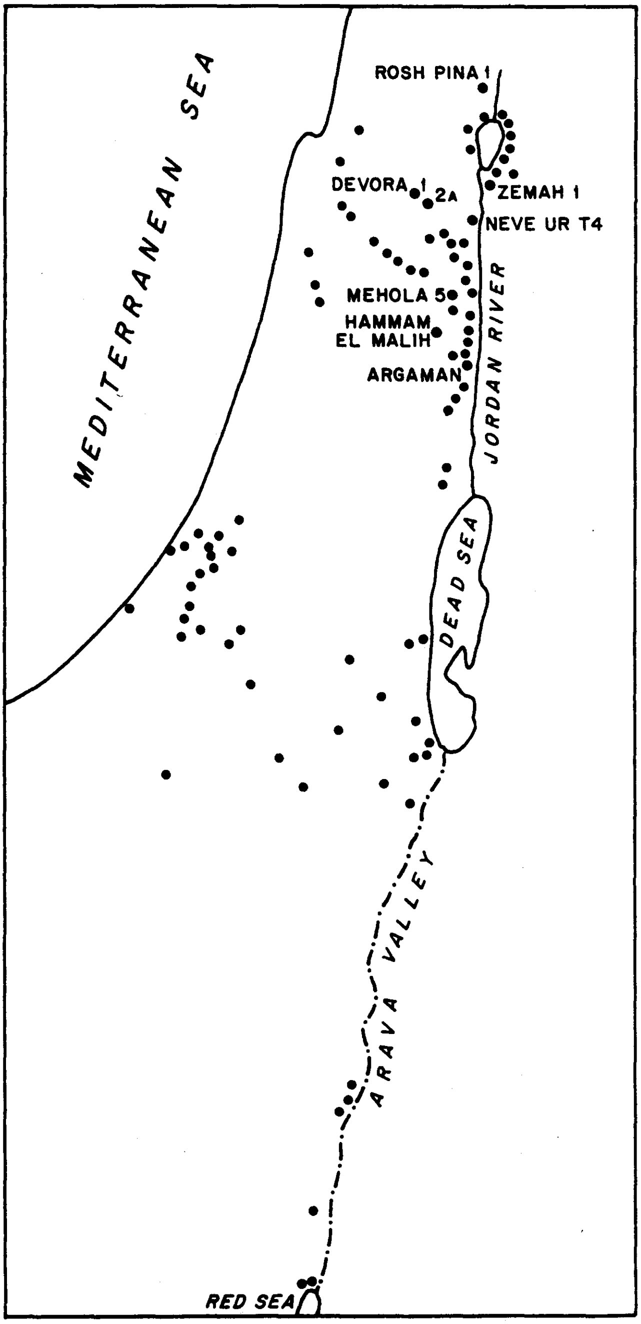

Figure 4: Occurrence of Ca-chloride groundwater in Israel.

Unlike the Devora-type brine, the Neve Ur water seems to be genetically related to the Neogene Sdom Sea that preceded the contemporary Dead Sea. This assumption is supported by the following facts: (1) Neve Ur water has never been encountered outside the limits of the Rift; (2) the water is usually phreatic or confined in Quaternary formations or at shallow depths and always overlies the heavier Devora-type brines; (3) their chemical composition and ionic ratios resemble those of the recent Dead Sea.

THE HAMMAT GADER PROVINCE

Four main springs emerge at the Hammat Gader site located on the northern bank of the Yarmouk river valley (Figure 3). It branches out eastward from the Jordan Valley and follows a regional synclinal axis striking NE. The springs flow out of a thick sequence of deeply faulted and fissured Lower Eocene limestones overlain by Neogene - Quaternary volcanics. The total outflow of these springs attains several hundreds m^3/h.

Hydrogeochemistry and geothermics: As indicated in Table 4, the four springs have different salinities and temperatures. There is a clear positive correlation between the levels of salinity, temperature, isotopic depletion and the age of groundwater.

The water of Ein Sahina stands out through its typical Ca-bicarbonate ionic assemblage, low salinity level and slightly elevated temperatures. At the other extremity is the Ein Maqle water which stands out because of its higher temperatures, high chloride, Na-chloride composition, the most depleted isotope values and oldest age. Mazor, *et al.*, (1973) and Gil'ad (1985) showed that all parameters referring to the four springs are on mixing lines between the two previously mentioned springs.

High resolution seismic reflection surveys followed by deep drilling carried out 4 km NE of the springs, enabled elucidation of the following hydrological model for the area which comprises basically the intermixing of three groundwater bodies:

(1) saline hot groundwater flowing in deep-seated Cenomanian - Senonian aquifer units,
(2) Ca-chloride brines,
(3) fresh water flowing in the Eocene sequence.

The recharge areas of the deep-seated Cenomanian - Senonian sequence are at a considerable distance to the north on the Hermon massif and southward, on the Irbid Plateau. The waters circulate at great depth, under confined conditions, and are therefore under considerable artesian pressure. They rise along faults mixing with highly diluted Ca-chloride brines and with fresh water from the overlying Eocene aquifer.

Deep drilling (Meizar wells 1, 2, 3 - Figure 3) revealed high BHT temperatures of up to 80°C at 1230 m. These temperatures indicate a thermal gradient of 1°C / 20 m. Such high values were also observed in the Zemah 1 wildcat well (located at the southern tip of Lake Tiberias - Figure 4) and in the subsurface of the Irbid Plateau.

State of utilization: Warm water emerging from the springs is exploited for balneological purposes. However, most of this water is used for shrimp- and alligator farms.

Table 4: Average chemical composition and maximum temperatures of thermomineral springs in the Hammat Gader area.

	Ein Sahina		Ein Reah		Ein Balsam		Ein Maqle	
	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)
TDS	658,9	17,51	955,6	28,40	1140	34,50	1534	47,82
Cl	82,50	2,35	224,8	6,42	300,9	8,60	527,6	15,10
SO_4	50,00	1,04	100,1	2,08	140,0	2,91	180,0	3,75
HCO_3	381,0	6,24	361,0	5,91	360,0	5,90	352,8	5,80
Ca	60,05	3,02	106,6	5,33	137,8	6,90	166,5	8,32
Mg	30,90	2,57	43,20	3,60	44,00	3,60	46,70	3,90
Na	50,40	2,19	111,2	4,83	145,0	6,30	240,2	10,44
K	4,05	0,10	8,72	0,22	12,50	0,32	19,90	0,51
Ionic sequence (meq/l)	HCO_3>Cl>SO_4 Ca>Mg>(Na+K)		Cl>HCO_3>SO_4 Ca>(Na+K)>Mg		Cl>HCO_3>SO_4 Ca>(Na+K)>Mg		Cl>HCO_3>SO_4 (Na+K)>Ca>Mg	
$rHCO_3/rCl$		2,65		0,92		0,68		0,38
$rSO_4/rHCO_3$		0,16		0,35		0,49		0,64
rSO_4/rCl		0,44		0,32		0,33		0,24
rMg/rCa		0,85		0,67		0,53		0,46
rNa/rCl		0,93		0,75		0,74		0,69
rNa/rK		20,90		21,95		19,60		20,47
Cl/Br		239,9		99,50		81,30		89,40
rQ		0,41		0,66		0,78		0,87
No. of samples		7		5		5		5
Max. temp. (°C)		28,0		38,0		42,0		52,0
pH		6,70		7,40		7,20		7,20
CO_2 free		--		92,00		93,00		100,0
H_2S		--		6,00		8,40		14,80
^{2}H		−30,80		−30,40		−30,60		−31,70
^{3}H		3,00		7,00		1,40		0,90
^{18}O		−5,75		−6,00		−6,35		−6,50
^{14}C		18,60		14,40		13,40		9,20
^{13}C		−14,10		−12,30		−11,40		−9,50
^{222}Rn		6340		7420		7180		2900
^{226}Ra		40,00		148,0		126,0		256,0

THERMOMINERAL WATERS IN ISRAEL - GENETIC PROBLEMS

According to Eckstein (1974, 1975), all springs characterized by anomalous temperatures are associated with existing fault patterns. Most springs emerge at intersections of secondary faults with the main lineations of the Rift system. It seems that the tectonic elements which control the occurrence of thermal springs also play an additional double role as water conduits. On one hand faults may act as flow paths for waters ascending from subsurface reservoirs. This may be the explanation for the unique grouping of springs along the still active fault lines of the Rift. On the other hand, they may act as conduits for down flowing meteoric water causing a cooling effect and changing the isotopic ratios of groundwater originating from deep seated reservoirs.

Eckstein (1975) indicated considerable variability of thermal gradients in various parts of the country. Values range between 1° to 10°C per 100 m of depth. However, in many localities in which low geothermal gradients were encountered, measurements were possibly affected by the vertical movement of groundwater. The proponents of the normal geothermal gradient theory (Mazor, *et al.*, 1969) assumed that water arrives at the surface with little or no decrease in temperature from its maximum values, and that the depth of circulation is indicated by the measured water temperature. Within such a system, the downward movement of cold meteoric water from the recharge area to the base of the circulation, must lower ground temperatures and hence the geothermal gradient. On the other hand, the water at the base of the circulation may be at temperature equilibrium with the surrounding rocks and reaches the surface at an appreciably higher temperature than that of the surrounding ground. Therefore, the normal gradient within this part of the system must be lower than that of the "normal, non-thermal" area outside the system (Eckstein, 1974). To date, no conclusive evidence pointing to the existence of geothermal anomalies due to an underlying shallow lava chamber has been discovered. The only exception may be the anomaly of Hammat Gader and of the Northern Irbid Plateau.

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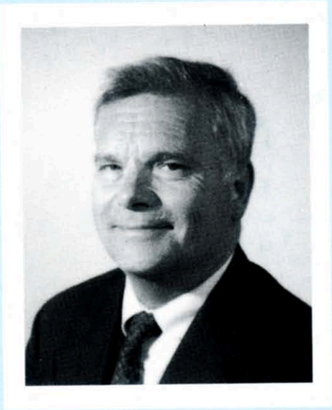

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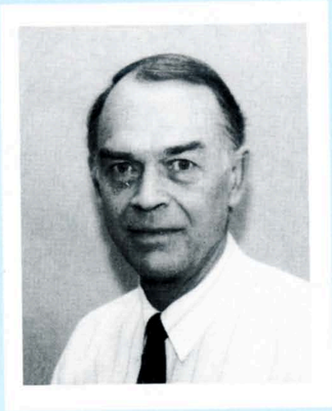

Ian Simmers

Since the 1970s mineral and thermal waters have attracted renewed interest as a useable natural resource. As a result, a reassessment of their therapeutic properties has called upon detailed hydrochemical and hydrogeological investigations in countries with a strong balneological tradition.

The subsequent development of hydrogeothermal resources during the same period has produced a wealth of data on the related waters. An update of this scattered information was set as an objective by the Commission for Mineral and Thermal Waters of the International Association of Hydrogeologists (IAH) in 1986.

A series of monographs, prepared along similar lines and concerning six european countries, is presented in this "*Hydrogeothermics*" volume (ICH vol. 15).

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