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# LECTURES ON GEOTHERMAL RESOURCES AND UTILIZATION IN POLAND AND EUROPE

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# PREFACE

Although geothermal energy is categorised in international energy tables amongst the "new renewables" (biomass, geothermal, solar, small hydro, tidal and wind energy), it is not a new energy source at all. People have used hot springs for bathing and washing of clothes since the dawn of civilisation in many parts of the world. Geothermal springs are an important part of our civilisation and history. The UNU Visiting Lecturer 2003, Dr. Beata Kepinska, has for many years been one of the leading geothermal specialists of Poland and Central Europe. She has not only been involved in the modernisation of geothermal research, exploration and development in Poland, but has also been one of the keen scholars who collect data and stories on our geothermal heritage and share this with professionals and the general public.

In her lectures presented to the UNU Fellows attending the 25$^{th}$ annual course of the UNU-GTP in 2003, she covered in an admirable way her many fields of interest and expertise. She dealt with geothermal energy in human history worldwide, with geothermal energy in contemporary balneology and tourism, with geothermal energy development in Europe as well as more specifically in Poland. She held the audience spellbound, and shared a lot of experience and insight into how geothermal energy has and will in the future benefit the people. We are very grateful to Beata for writing up her lecture notes in such an excellent way and thus make the lectures available to a much larger audience than those who were so fortunate to attend her lectures in Reykjavik. We are very proud of Beata being a former UNU Fellow (in 1994). She is the third UNU Fellow who is invited to be the UNU Visiting Lecturer

Since the foundation of the UNU Geothermal Training Programme in 1979, it has been customary to invite annually one internationally renowned geothermal expert to come to Iceland as the UNU Visiting Lecturer. This has been in addition to various foreign lecturers who have given lectures at the Training Programme from year to year. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal specialists have found time to visit us. Following is a list of the UNU Visiting Lecturers during 1979-2003:

| | | | |
|---|---|---|---|
| 1979 Donald E. White | United States | 1992 Patrick Muffler | United States |
| 1980 Christopher Armstead | United Kingdom | 1993 Zosimo F. Sarmiento | Philippines |
| 1981 Derek H. Freeston | New Zealand | 1994 Ladislaus Rybach | Switzerland |
| 1982 Stanley H. Ward | United States | 1995 Gudm. Bödvarsson | United States |
| 1983 Patrick Browne | New Zealand | 1996 John Lund | United States |
| 1984 Enrico Barbier | Italy | 1997 Toshihiro Uchida | Japan |
| 1985 Bernardo Tolentino | Philippines | 1998 Agnes G. Reyes | Philippines/N.Z. |
| 1986 C. Russel James | New Zealand | 1999 Philip M. Wright | United States |
| 1987 Robert Harrison | UK | 2000 Trevor M. Hunt | New Zealand |
| 1988 Robert O. Fournier | United States | 2001 Hilel Legmann | Israel |
| 1989 Peter Ottlik | Hungary | 2002 Karsten Pruess | USA |
| 1990 Andre Menjoz | France | 2003 Beata Kepinska | Poland |
| 1991 Wang Ji-yang | China | | |

With warmest wishes from Iceland,

Ingvar B. Fridleifsson, director,
United Nations University
Geothermal Training Programme

## ACKNOWLEDGEMENTS

Europe is an important continent as far as geothermal resources and their implementation are concerned. The countries and places having long geothermal history are gradually joined by the new ones. What's more, apart from traditional technologies and methods, there are being introduced new solutions and options in Europe, also in its Central and Eastern parts.

The author is very grateful to the Director, Dr. Ingvar B. Fridleifsson and the Studies Board of the UNU Geothermal Training Programme for the invitation to deliver lectures on some selected aspects of geothermal development in Europe in the very special year of the $25^{th}$ Anniversary of the UNU-GTP. I am particularly glad to have had an opportunity to present geothermal attempts and achievements in Poland – my home country, to international audience.

The lectures were prepared thanks to the kind help of several persons who provided useful information and figures. These were some former Polish UNU-GTP graduates: Maria Gładysz, Piotr Długosz, Ewa Kurowska, Jarosław Kotyza, Zbigniew Małolepszy and Leszek Pająk. Thanks are also due to Prof. Roman Ney, Antoni P. Barbacki, Wiesław Bujakowski, Jacek Kurpik, Zdzisław Malenta, Radosław Tarkowski, Barbara Uliasz - Misiak, and Lucyna Zimer - Skarbińska. I am obliged to Prof. Wojciech Górecki for providing the most recent publication. Klara Bojadgieva (Bulgaria) and Peter Seibt (Germany) kindly delivered data on geothermal issues in their countries. Let me also thank Jolanta Lepiarczyk for translations, Maria Victoria Gunnarsson and Ludvik S. Georgsson for final linguistic corrections and editing the manuscript for printing.

Beata Kępińska

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# LECTURE 1

# GEOTHERMAL ENERGY IN HUMAN HISTORY, CULTURE, AND PRACTICES – SELECTED HIGHLIGHTS

## 1. INTRODUCTION

In everyday practice, geothermal energy is treated both by us - professionals, and regular users as one of renewable energy sources. Although we tend to concentrate on its utility and technical value, geothermal is also part of our civilization and history. Therefore, it is worthwhile to spend some time investigating this kind of energy to learn its role and place in historical and cultural heritage of the World. This lecture is the result of personal interest of the author in geothermal in view of its technical, natural and also humanist and social aspects, which allure new geothermal enthusiasts, and inspire specialists with new ideas. The gathered knowledge not only demonstrates the variety of relations between man and energy of the Earth, but also to the beauty and unique character of this element of our Planet.

A number of ideas related to the man-geothermal energy relationship are enclosed in “Stories from a Heated Earth. Our Geothermal Heritage” (Cataldi et al. [eds], 1999). Many cases presented in this lecture have been taken from this book. This is a genuine and unique source of information about the world’s geothermal energy with a broad historical and cultural background. All geothermal specialists should put this publication on the obligatory list. The use of geothermal water and steam for bathing and health care has had a long tradition in many regions of the world. It goes back thousands of years and has contributed to the development of the material culture, myths, and beliefs among many civilizations and nations. People living in the vicinity of geothermal manifestations took advantage of geothermal springs instinctively and naturally; in the same way they benefited from energy of the sun, water, and wind. This was done with respect to nature or the divine powers, which according to the beliefs, manifested through these phenomena.

Nowadays, hydrothermal phenomena such as hot springs, geysers, as well as other surface evidences of geothermal activity are unique natural and tourist attractions. Indeed, the world’s first national park – Yellowstone (USA) was established in 1872 for the purpose of protecting, preserving, and providing proper tourist access to natural hydrothermal phenomena. Today, geothermal energy plays many different functions in tourism, from ecological heating of hotels and resort facilities to the use of geothermal waters in recreational and therapeutic pools, as well as curative and therapeutic procedures. Its growth in this “geothermal” direction will facilitate the “sustainable tourism” and ecological development of many regions and countries. Recreation, rest, and health are among the basic areas of direct use of geothermal energy. In many countries, this is an essential component of the tourist industry in its broad sense. According to the data presented at the World Geothermal Congress Japan 2000, geothermal fluids and energy are used for bathing and recreation in over 50 countries, which amounts to more than 11% of total installed power and 22% of thermal energy consumed overall annually in direct applications throughout the world (Lund and Freeston, 2000).

The paper indicates some selected historical and cultural highlights of relationships between human and geothermal energy. It gives also several examples of contemporary geothermal balneotherapeutics and bathing – a field of geothermal use which combines strictly utilitary as well as various cultural and social aspects. Furthermore, the significance of this type of geothermal applications for tourism in several selected countries is presented, involving economic and marketing aspects and issues which are generally not well known. Some contemporary tendencies of development in this sector of tourism are also pointed out. For many regions, this is a long-term opportunity for development in such areas as balneology, recreation, or agrotourism. The countries and regions described in the text are marked on Figure 1.1.

Certainly, one of the best examples of the numerous man-geothermal energy relationships, and use for balneotherapy, recreation and many others, is Iceland. All foreign visitors, including the UNU Geothermal Training Programme Fellows have a unique chance to learn, experience and hear from the Icelandic people about geothermal energy, and how to take advantage of it.

The author hopes that the subjects presented in this lecture enrich and broaden the strictly scientific, technical and economic aspects of the activities aimed at practical use of geothermal energy, thus making it more user-friendly and understandable, as well as indicating its role in the development of civilization and contemporary life.

FIGURE 1.1: The countries and regions mentioned in the text (marked by the asterisks)

## 2. PREHISTORIC ORIGIN OF MAN - GEOTHERMAL ENERGY RELATIONSHIPS

Utilitary, rational, and also spiritual relationships with geothermal phenomena developed at the prehistoric stage of human development. The first relations between man and geothermal energy date back to the Paleolite period (Quaternary times up to 14,000 B.C.), when man might have discovered the advantages of warm springs and started to use them. This could have taken place in the following order: thermal bathing, geothermal cooking, and balneotherapy – healing of wounds and recreation (Cataldi, 1999).

The numerous Neolite (7,000 to 3,000 BC) archaeological findings evidence the use of thermal waters by man. Men used to settle in the vicinity of geothermally active places, where they could bathe, rest, cook or use hydrothermal or volcanic products. Reconstructed pictures from the Çatal Hüyük cave in Turkey (Özguler and Kasap, 1999) show volcanic eruptions, outflows of waters and steam emanations. Man used to settle also near hot springs. Traces of this could be found on the Japanese islands 11,000 years B.C. (Fridleifsson, 2000), whereas archaeological findings on the Asian continent show the use of hot springs for bathing as far back as 5,000 years B.C. (Lund, 2001a). Greek islands abound in examples of thermal energy use for therapeutic and cosmetic purposes, as well as geothermal by-products; e.g. in Crete, some skin problems were cured by bathes in thermomineral muds. Hot springs were also part of religious rites and beliefs in Egypt, Palestine and Israel.

In the Bronze Age (3,000 to 700 B.C.), the Etruscans – historical "fathers of geothermal industry" developed their civilization in the central part of Italy (1,200 to 300 B.C.) (Cataldi and Chiellini, 1999). Many Etruscan settlements and cities were established in the places of springs, geothermal manifestations, and products of hydrothermal activity. They were of great economic value to the Etruscans. The Etruscans achieved a high level of trade, metal working and handicraft. They also developed mining. In the area of the present Tuscany, they excavated the ores of a number of metals, e.g. silver, copper, iron, lead, zinc; they exploited alabaster, and also other minerals and hydrothermal products, e.g. alum, borate, kaolin, iron oxides, sulphur, silica, travertines, and thermo-mineral muds. They abounded in the triangle of Pisa, Siena and Grosseto. These minerals were mainly used for the production of pottery, enamel, paints, dying of glass, wool and cloth, production of ointments and other medicines. The Etruscans developed many of their own original technologies, e.g. covering pottery with enamel. The enamel was made of borax, which was recovered from boraciferous springs (still active in the Larderello region, Italy). Travertines and alabasters were a precious material used in art, sculpture, and construction.

In ancient times, the Etruscans were most active in the recovery, processing, and use of geothermal products. They were also known for their trade in the Mediterranean Basin, thus popularizing many of the hydrothermal products. Apart from economic and social aspects, the Etruscans valued hydrothermal waters and products for their healing properties. They developed many healing methods, employing geothermal waters as well as salts and thermo-mineral muds (even today these products are applied in balneotherapy in the Toscanian centres; Cataldi, 1999). They developed practises of geothermal bathing and balneotherapy, thanks to which the first public baths could be established (*balnea and thermae*). They made water intakes, built pools, and surrounded them with paid recreation and leisure objects. Actually, it was the Etruscans who developed versatile and multi-scale use of geothermal energy.

## 3. GEOTHERMAL ENERGY IN HISTORY, MYTHS AND TRADITIONS THROUGHOUT THE WORLD – SOME FACTS

The place and role of geothermal energy can be found in history, culture and myths and traditions of many countries on various continents. Several cases from Africa, Asia, the Americas, Oceania, and Europe are presented in this chapter. They are so prominent that they cannot be ignored even in a very general paper.

### 3.1 Africa – the Great Rift and the myth of the phoenix

The eastern part of Africa is crossed by the Great East African Rift – one of the most spectacular and important rift zones of our planet. Active volcanoes, volcanic lakes, hot springs and hydrothermal deposits are typical of this area (Lund, 1999). The Great Rift is often called a cradle of the human race. The pre-human remains of Australopithecus anamensis, the earliest known human ancestors dating back to about 4 million years, have been discovered within the Rift area, in Northern Kenya. Traces of successive, younger human ancestors have been found there, too.

Millions of years later, the Africans incorporated geothermal and volcanic phenomena into their religious beliefs, often treating their manifestation as sacred places of spiritual importance. Many myths, legends, and tales were handed down from generation to generation. Among the most spectacular phenomena within the Great African Rift is the system of warm alkalic lakes, from Lake Natron to Lake Nakuru, in Kenya and Tanzania. These lakes are associated with a unique population of flamingos, who adjusted to extreme conditions. The temperatures of water in lakes and adjacent springs are up to 60ºC, and waters are highly alkaline (up to 10.5 pH). It is assessed that about 4 million of these birds live there. They live on blue-green and reddish algae, abundantly growing in shallow and warm lake waters.

A version of the myth about the phoenix – an immortal bird resurrected from the fire - incorporated the idea of the scarlet-coloured flamingos and lakes. This myth was based on the fact that flamingos incubate their eggs in hot mud accumulated in the shallow waters of the lakes and surroundings. According to Lund (1999), "long ago when people saw young flamingos emerging from the lakes to their first flight they thought they saw resurrection of the phoenix coming for a drink at the shore".

## 3.2 Asia

### 3.2.1 Cult of geothermal waters in India

Like in ancient times, contemporary inhabitants of India are strongly attached to their religion and beliefs. Siva is one of the most prominent gods, whose cult is related with sacred hot springs, given by gods to man. In India, there are over 320 geothermal springs now. They are related with the active zone of tectonic subduction of continental plates (Chandrasekharam, 1995). Man's settlements were generally established far away from hot springs – sacred places could not be inhabited! The small village of Devnimori in the state of Gujarat is an exception. According to a legend, one of the hot spring gods descended to Devnimori and the grateful village people started to worship this holy place by erecting numerous temples. This was a place of pilgrimages. The cult of Devnimori has lasted until the present day. People worshipped the hot springs and were aware of their therapeutic value. Special attention was paid to the possibility of restoring physical, but before all spiritual and intellectual powers. Baths in thermal waters, considered a religious rite, were joined with a variety of religious ceremonies and prayers in the nearby temples. Mass pilgrimages to sacred hot springs and the protecting temples were undertaken as a beginning of "therapeutic tourism" and "pilgrimage tourism", popular in many regions of the World even nowadays.

In the 20$^{th}$ century, in the years 1940 to 1950, some of the geothermal springs considered as not sacred and which were not cult places, were subjected to chemical experiments. The quality and chemical composition of many of them was compared with mineral waters brought to India by Englishmen from the European countries (!). Some of them were classified as fit for therapeutic purposes or as mineral or table waters. Then they started to be bottled and sold on a local market (Chandrasekharam, 1995).

### 3.2.2 Geothermal waters in Chinese medicine

Chinese traditions of geothermal water usage date back to at least 3,000 B.C**.** Such waters were used for watering cultures, washing, cooking and for therapeutic purposes. Li Shi-zhen, a famous physicist of the Ming Dynasty (1368-1644) advised: "*the best cure for illnesses is a bath in hot springs*" (Wang Ji–Yang, 1995). Like in many countries throughout the World, there are many Chinese myths and legends related with hot waters.

The Chinese wanted to learn about the origin of springs and other geothermal phenomena. In the process of explaining them, they frequently managed to arrive at strikingly correct geological and scientific observations, e.g. one of the poets of the Song Dynasty (1127 to 1279) writes: "*in the places of mountains of fire [volcanoes], you may surely look for hot springs*" (Wang Ji–Yang, 1995).

Some of the geothermal springs had a strategic significance and were not imparted to civil population. They could be used only by the army. Jiunquan – Golden Intake in Gansu Province (near the Silk Trail) was attended by soldiers wounded during the wars of the Han Dynasty (140-117 B.C.). In 644

A.D., during the Qin Dynasty, springs were used for recreational purposes. A special palace was erected in Tangquan, where apart from baths, people could also heal their ailments by drinking water from special holes in the rock. The palace was reconstructed several times, to achieve the most luxurious form during the Tang Dynasty in the year 747. A number of facilities were built, including a new pool for the personal use of the Yang Gui–fei emperor's mistress. She used to come there with her court to enjoy the healing baths. There was a joke describing the life of the mistress: "*If you bathe in the Huaqing springs, you will feel much better. They will clean you of all the filth, just like Yang Gui–fei cleanses away the paint from her face*" (Wang Ji–Yang, 1995).

There was, however, another way of using geothermal waters in China. Frequently low-mineralized, tasting like drinking-water, geothermal waters found their place in the famous "wine, liquor and tea culture". They were used for the production of wine, liquors, and tea. The famous high-quality Maotai liquor, Qingtao beer, and Zhangyu wine were made using geothermal waters. Tea was specifically made of Hupao – Running Tiger spring, which had the purifying qualities, restored physical and spiritual strength, and before all was exquisite in taste! Traditional Chinese medicine is famous for water therapy. The so-called "cold" diseases, e.g. artretism, rheumatism and all kinds of problems with mobility should be treated with warm water (geothermal waters were used as a rule). All diseases accompanied by high temperature had to be treated with cold water. No warm spring water could be used in such cases. All skin diseases were treated with sulphided waters. Other types of water were not recommended. The accuracy of diagnosis is amazing! Also contemporary geothermal spas and recreation centres in China widely use both traditional methods of curing and traditional architectural patterns (Figure 1.2).

FIGURE 1.2: Beijing, China – traditional Chinese entrance gate to the Jiuhua spa using geothermal water for healing and recreation (photo B. Kepinska)

### 3.2.3 Geothermal bathing and healing treatment in Japanese courts

Japan is located on volcanic islands, therefore abounds in warm springs, steam emanations, and other geothermal phenomena. Just like in other countries, there are many myths, beliefs, and legends about geothermal and volcanic manifestations. The oldest centres of Japanese culture were sited near the hot springs. Among the oldest ones were Yuda springs (Iwate), dating back to 11,000 B.C. (Fridleifsson, 2000). The first records documenting geothermal medicine and recreation come from 794 A.D. The development of these two domains reached a very high level, frequently owing to the contribution of the successive dynasties (Sekioka, 1995).

Geothermal sources gave birth to the construction and development of many spas visited by Japanese noblemen for therapeutic and recreational purposes. One of the oldest preserved documents on geothermal comes from 998 A.D. It reports on a visit of a Japanese lord to hot springs near Nagano to improve his health. In the successive years and centuries, numerous geothermal spas started to be visited by crowds of samurai, gentry, and royal court members. Geothermal waters were so popular that in the Kamarura times (1192-1393), water from some springs was put into barrels and transported to the royal castle in Kyoto (even to 100 km of distance). Also, warriors returning from wars used geothermal springs for healing their wounds.

Over centuries, a number of temples have been erected devoted to the hot springs and their gods. Sacred springs and temples had a positive influence on the development of the pilgrimage movement. The main routes led to the spas, which started to develop and grow in a number of places where the travellers could rest and eat. New water intakes were made and the old ones improved to provide good conditions for religious practices and for healing baths.

Edo time (1603 - 1868) was most favourable to the development of geothermal spas. According to the old documents from 1644, the emperor and his court had been sent water from selected springs several times a year. Each time, the water was transported in barrels of 300 $m^3$ capacity for bathing. This custom became so popular that the authorities of one of the cities in Ishikawa started to profitably sell geothermal water at very high prices to Kyoto, Osaki, and Edo (now Tokyo). In 1710, the first medical books describing baths in hot springs, their curative properties, popular spas and the offered treatments were published. These books were a kind of guide for tourists informing them about places worth seeing in the vicinity of the spas, advising on the souvenirs, etc.

Studies were also made on therapeutic properties of geothermal waters. In 1734, Doctor Konzan Goto selected Kinosaki spa and studied it for its therapeutic properties. He observed good results of treating chronic diseases with hot water. The symptoms could be much reduced by applying an appropriate hydrotherapy (Sekioka, 1995). Even now this approach is still used in balneology.

### 3.3 Oceania - geothermal energy in the life of Maori in New Zealand

The life of Maori – the native population of New Zealand – has always been closely connected with nature, and so with the geothermal and volcanic phenomena, in which the country abounds. All natural resources used to be treated as precious gifts of the gods, deposited to them to be later handed down to the next generation. The Maori had a holistic approach to geothermal energy. They knew that energy was generated underground, and it also had its surface manifestations, e.g. hot springs, geysers and other manifestations, being the “eyes” or “face” of the geothermal system. A combination of myths and beliefs, closely connected with “sacred rules” was an efficient protection of all geothermal phenomena against any kind of misuse. Maori families and tribes lived in strictly defined areas of geothermal activity; crossroads and meetings places were often made at geothermal springs. The “guardians” played a special role. They lived in the vicinity of the springs, taking care of hot waters on behalf of the whole family or tribe. Or, to express it in our words, Maori used to protect the environment and natural resources, preserving utility and spiritual properties for the future generations. They were forerunners of the idea of “sustained development” and preservation of national heritage. It is worth noting that Maori did not want to overtake the white culture, therefore, consequently refused to share geothermal phenomena with white people as they were sacred (Severne, 1995).

Waters and other geothermal phenomena were an integral part of life of Maori, who were born and lived there; they bathed, cooked, relaxed, heated and socialized near geothermal manifestations and were prepared for their last journey. Maori classified and named the geothermal, hydrothermal, and volcanic phenomena (just like the Icelandic people did on their island in another part of the globe).

„Taha wairua" is a spiritual aspect of the Maori, according to which the Maori were obliged to keep their bodies and spirits in a good condition. All natural springs were considered to be "taonga", i.e. purifying. One of the first functions of geothermal waters was healing. Other ones were related with rest and heating. Apart from this, geothermal heat was used for cooking and stewing of food suspended in special baskets in geothermal steam. This aspect has remained important for the tourists coming to Maori.

Maori also developed cures for various diseases with the use of hydrothermal waters and products. Many healing methods and rites have remained sacred for a number of tribes and thus kept in secret. Skin diseases were cured with ointments made of animal fat and sulphur near the springs. Maori knew that different types of geothermal waters could be used for healing different kinds of illnesses. Therefore, they selected special ponds where specific diseases were cured. Only patients suffering from the same disease could use the same pond.

In 1840, representatives of Maori and the British Queen signed the so-called Waitangi treaty, according to which the natural resources of New Zealand were treated as "taonga katoa" – Maori treasure which could not be overtaken by anyone. It incorporated Maori language, cultural heritage, customs handed down and preserved for the future generations. Although Maori treated geothermal and volcanic phenomena in a very special way, the government authorities were less attached to them. In spite of many efforts, the ownership of geothermal resources has not been regulated by law yet, and the Maori insist on being their only proprietors.

In the middle of the 19$^{th}$ century, geothermal phenomena started to be a tourist attraction, e.g. famous purple and white terraces of Otukapuarangi, as well as hot springs and geysers. Some tribes were involved in the tourist movement as, e.g. guides. Nowadays, geothermal phenomena are one of the main tourist attractions in New Zealand because of their beauty and also unique relation with history, culture, and everyday life of its inhabitants.

### 3.4 The Americas - religious and utility aspects of geothermal energy for native inhabitants

North, Latin, and South America abound in areas of geothermal activity. They are mainly located on the western part of the continents and are related with the zones of subduction of continental plates. Archaeological findings show that man's settlements were established near the hot springs in North America as far back as 10,000 years ago (Lund, 1999). Geothermal springs and other phenomena in the Americas were sacred places of worship where spirits resided. Volcanic and hydrothermal phenomena were subjects of numerous myths like, for instance, myth and cult of the cruel goddess Pele in Hawaii. Areas with hot springs created shelters and asylums for warriors during their tribal wars.

The relationship of Indians – native inhabitants of the Americas – with geothermal phenomena covered the area from Alaska, through Mexico to Bolivia, Peru, and Chile (Calderon, 1999; Suarez and Cataldi, 1995). It is enough to mention that the Aztecs and Incas living in these areas developed one of the most advanced civilizations, as did the Indians of North America, inhabiting the areas known today as The Geysers and Yellowstone. Life, customs, and beliefs of the Incas living in the high mountains of the Andes were closely connected with various energy manifestations, e.g. earthquakes, hot springs, fumaroles, etc. The first descriptions of geothermal applications by Incas for bathing and healing were made by the Spanish conquistadors, historians, and missionaries. They saw a great number of palaces and temples built near natural geothermal ponds and hot springs which were equipped with bathing facilities with hot and cold water supplied through a system of pipelines. Both aristocracy and common people could enjoy baths in warm spring waters. Pools and bathing facilities were described, e.g. in Cuzco – the latest capital of the Incas. What the Spaniards saw in Cajamura province after defeating King Atahuallpa in 1531 was luxurious royal geothermal baths capable of serving crowds of people. The conquistadors paid special attention to the rich decorum of the baths' interior. They robbed all precious elements of the equipment and belongings of the visitors. Geothermal springs played a very important role as places of religious rites (Calderon, 1999). Just like the Etruscans and other inhabitants of the Mediterranean area, hydrothermal and volcanic products, e.g. obsidian, chalcedony, and rock crystal were sold or used as money by the Indians.

A number of names in the Pre-Columbian Americas were related with geothermal phenomena. And so, in Mayan language the names of many towns referred to geothermal characteristics of a place, for example: Popocatepetl (popoa, "steam"; tepetl "hill") – volcano, or Atotonilco (a[tl], water; "totoni" [li] hot; "co", place) – means "place in the hot water" (Hernandez Galan et al., 1999). The origin and meaning of these words correspond to the Icelandic "Reykir" or "Reykholt" known also to all the UNU-GTP Fellows.

In North America, special attention should be paid to Yellowstone and The Geysers. Yellowstone was the first national park in the world established by president Ulysses S. Grant in 1872 to provide protection, preservation, and popularization of natural hydrothermal phenomena. Today, in over 10,000 spots, the visitors may see active geysers, hot springs, boiling ponds, mud geysers, steam emanations, and colourful secondary mineral precipitations from hot waters and steam. Yellowstone covers about 9,000 km$^2$, and is the biggest national park in the U.S.A., a Biosphere Reservation and center of the World Geological Heritage. Thus, one may conclude that the history of environmental protection has been related with geothermal energy from the very beginning.

Before the coming of the first white settlers in about 1800, The Geysers were inhabited by some Indian tribes who divided the area among themselves. The geothermal manifestations were treated as sacred and used with great care. Shamans were very proficient in making medicines based on geothermal waters and hydrothermal products. The Geysers gave birth to organized tourism in the U.S.A. Local Indians were the first guides, who accompanied the white tourists but refused to enter certain places and canyons with geothermal manifestations, as protected by evil spirits. In 1840 to 1850, the region started to be developed. Hotels and roads for coaches were built, adding greatly to the popularization, and consequently, profitability of this region. Crowds of tourists started to come. In 1890, somebody wrote: "*these famous springs are admired and enjoyed by thousands of people coming here each year*" (Hodgson, 1999).

## 3.5 Europe

### 3.5.1 Greece – geothermal energy in a cradle of European civilisation

Abundant warm springs and other geothermal and volcanic phenomena greatly influenced the life of ancient Greece – a cradle of European civilization, a civilization that greatly contributed to the development of culture and science in the World's history. For centuries, they inspired many myths, religious beliefs, raised scientific interest in their description, understanding, and practical implementation. It was Greece where balneology was born as a science. This interesting, multilayered subject can only be outlined and exemplified by evidences deeply rooted in the European and world cultural and historical heritage.

*The myth of Atlantis – a "lost" continent.* The myth of Atlantis, a famous "lost" continent, forms an unusual combination of legends as well as geological and historical facts. It is known, thanks to Plato – great philosopher, scientist and teacher (427 – 347 B.C.), who wrote down all the oral relations handed down from generation to generation. Although there are many speculations and versions, and the investigations are in progress, the "lost" continent is believed to be a Greek island Thera (now Santorini) destroyed by an enormous eruption about 1628 B.C. As a result of the literary idea of Plato, it was believed that the continent was "larger than Libya and Asia [i.e. little Asia – known to Plato] together" (Fytikas et al., 1999). However, during the eruption a large portion of land, about 4x8x1 km sank. Plato's descriptions of a high culture in the Thera island and its riches certainly could be attributed to the Minoan civilization on Crete island which may have been destroyed by a tsunami, a result of a huge explosion of the Thera volcano. Since 1628 B.C., volcanic episodic activity at Thera has occurred several times, most recently in 726 A.D. The island and the islets continue to be geothermally active and extremely popular for tourists. They are also the subject of various volcanological and archaeological investigations, carried out to unravel the mystery of Atlantis some day.

*Development of advanced balneotherapy.* It was the Greeks who wrote the motto "health through waters". It was then overtaken by the Romans and known so far as "spa" – "salus per aquis" (Fytikas et al., 1999). The word spa is used today to name thermal springs, health resorts (both with warm as well as cold waters) and a wide spectrum of related facilities. Balneotherapeutic practises in Greek mythology were the domain of gods and heroes of Mount Olympus. However, there were also "regular" people who took advantage of water treatments. In this context, one should recall Hippocrates of Kos – the first physician who used thermal waters for curing his patients (Fytikas et al., 1999). A number of thermal stations were dedicated to Asclepios – god of medicine, and the treatment was accompanied by prayers in dedicated temples. One of the best known places dedicated to Asclepieion (Hierapolis) lies close to Pergamon, now in Turkey. It was flourishing during the Hellenistic times (Section 3.5.3). Greece in antiquity was a centre where geothermal bathing and balneotherapy developed and propagated to the Mediterranean area.

*Greek and Roman literature and mythology.* Geothermal springs and other geothermal and volcanic manifestations found their places in ancient literature and mythology. They were mentioned and described by many famous Greek (and then Latin) poets, philosophers and scientists including Homer (7th century B.C.), Hippocrates (460 – 377 B.C.), Plato (427 – 347 B.C.), Aristotle (384 – 322 B.C.), Pliny the Elder (23 – 79 A.D.) and many others (Fytikas et al., 1999).

*The use of geothermal by-products.* The Greek mainland and Greek islands abound in volcanic and hydrothermal by-products. The most important was obsidian from Milos island where its exploitation probably started in the 3rd millennium B.C. The volcanic glass – obsidian was used for producing a wide variety of tools (Fytikas et al., 1999). It was exported to Crete, Cyclades islands, Macedonia, Thrace, and Anatolia. Among other hydrothermal by-products used were bentonites, kaoline, silica, sulphur, ore minerals, and travertines. In many cases, the tradition of mining some of them is still being continued, as in the case of bentonite and kaolinite mined on Milos island (Figure 1.3).

*Historical importance of geothermal localities.* Some geothermal stations in ancient Greece were so crucial in history that their fame extended to the present times. As an example, one can mention Thermopylae – a narrow gorge near the Tessaly coast in front of the Eubean Straits. The name of this gorge came from a cluster of warm springs used there for healing. However, this place is renowned for one of the most famous battles of the Antiquity. This war against Persian invaders took place in 480 B.C. (Fytikas et al., 1999). A small group of 300 warriors headed by the king of Sparta Leonidas bravely fought to the last drop of blood with the enemy to stop the Persian invasion on Greece. Thermopylae is regarded as a symbol of patriotism and brotherhood in the service of Greece. What can also be added about geothermal springs in Thermopylae – they are still active and used for healing purposes.

### 3.5.2 Rome and Italy – from thermal baths to the first geothermal power station

Italy has a considerable potential of geothermal waters and steams. Presently, it is known for a variety of geothermal applications, but thermal baths are its trademark. In the Roman Empire times, geothermal reached such a high level that it was treated as a place fit for rites, leisure, as well as social

FIGURE 1.3: Milos island, Greece – a mine of bentonite and kaolinite. These hydrothermal deposits have been mined there since the ancient times (photo B. Kepinska)

and political life. The Etruscans were the first to use thermal baths. Their tradition was overtaken and perfected by the Romans, who also employed the Greek traditions and patterns. Since the Medieval times, scientific bases of geothermal and geothermal industry have developed in Italy. In 1904, the world's first geothermal power station was started in Larderello (Cataldi and Burgassi, 1999a; Cataldi and Burgassi, 1999b; Burgassi, 1999).

In the 2nd century B.C., with the development of the Roman civilization, baths and bathing places started to be built. They were supplied with natural warm spring waters or heated water. The baths were used for washing, rest, sport, relaxation, and team plays. What is more, additional facilities and places created favourable conditions for social, business, and political meetings. Baths were equipped with libraries as well as special places for meditation and discussion. The interiors of the bathing places themselves were works of art covered with mosaics, handicraft, and sculptures. They had a spectacular layout where the individual parts could be used for specific activities and therapies. They played special functions in the bathing rites and the accompanying activities (Cataldi and Burgassi, 1999b).

FIGURE 1.4: Tivoli, Italy – health resort founded by the Romans. A fragment of a garden where geothermal water is used for various arrangements and fountains (photo B. Kepinska)

In Rome, the capital of the empire, over a thousand thermal baths existed during the peak period of bathing in the 3rd century A.D. A variety of services of various standards were offered to the visitors representing all social classes. Trips to baths in other cities close to Rome were another attraction (Cataldi, 1995; Cataldi and Burgassi, 1999b). These places were frequented by the Roman emperors. In the Medieval times, even popes used to visit such places as Tivoli (Figure 1.4). Military camps were built in such places that thermal waters could be used for massages and healing wounded soldiers. With time, some of these camps turned into spas. Thermal baths played a significant role in forming municipal societies, and establishhing trade and market relations. Leading numerous wars, the Romans brought their tradition of thermal baths to a number of the Mediterranean countries, as well as to the northern part of Europe (presently, e.g. Hungary). Ruins of Roman baths (thermae) are an important part of the ancient culture and tradition. Among the most famous ones are the Caracalla's therms in Rome, where concerts and other cultural events are organised.

Geothermal springs and other manifestations are related with the cult of numerous Roman gods and divinities. Those springs, giving health and wellbeing, were treated as sacred. Statues of the most important gods from the Roman Parthenon were put in the temples established near the bathing places. The Romans also used the hydrothermal by-products. In Rome, travertine was used for the construction of the Colosseum and Caracalla's therms.

A number of municipal centres in the present Italy were formed in the prehistoric times. Many consular roads overlapped older Etruscan roads leading to the geothermal manifestations. What's more, some of the cities keep on developing their tourist and therapeutic character in the present times, e.g. in Bologna region where several cities make use of geothermal waters, offering therapy, leisure and sport to the visitors.

Since the early Medieval times, the Italians had developed scientific and utilitary interest in geothermal energy. The main centres related to geothermal use concentrated on the Larderello region in Tuscany. This region abounds in geothermal manifestations and reservoirs. The first contemporary author of scientific surveys on Larderello was Ristoro d'Arezzo, who in 1282, described local hot springs and steam emanations. In the 16th century, the region of Larderello was analysed by a German physician Georg Bauer (1495-1555), commonly known as Georgius Agricola – "father" of mineralogy. Between the 16th and 19th centuries, further surveys were made by researchers, engineers and physicians all over Europe. They gave rise to geothermal geology and geothermal industry in particular. In the latter case, it was especially important to learn the nature of boric acid – a typical component of the local hot springs, commonly used for making medicines at that time (Cataldi, 1995; Burgassi, 1999).

From the technological point of view, the studies and experiments resulted in the development of practical management of geothermal energy and the genetically related raw minerals, e.g. recovery and processing of minerals and some chemical compounds from geothermal springs, in the technology of boric acid production, use of geothermal steam for driving pumps and mechanic engines, heating of industrial buildings, residential housing, and greenhouses.

In 1904, the first geothermal power station was launched in Larderello (Figure 1.5) (Burgassi, 1999). Now, apart from the local museum of geothermal industry, it is a great tourist attraction, where "geothermal souvenirs" can be bought, e.g. copies of 19th century lithographs showing geothermal manifestations in Larderello. Apart from Iceland, the Larderello region belongs to the most important of the World's tourist places where one may learn about the nature and possibilities of versatile management of geothermal energy.

### 3.5.3 Turkey – descendant of the Roman baths

Owing to its geotectonic location, Turkey abounds in geothermal waters and steams. Old traditions of geothermal utilization are deeply rooted in myths and history. The oldest prehistoric traces documenting geothermal applications - wall paintings in Çatal Hüyük cave - come from the area of the present Turkey. They are 12,000 years old (Özguler and Kasap, 1999).

The custom of thermal bathing and cult of warm springs flourished in the area of present-day Turkey during the Hellenistic and Roman periods. The Romans had a great contribution to the Turkish baths, both in the architectural and social aspects. It happened mostly during the Seljukin (1071-1308) and Ottoman Empires (1299-1308). The traditional Turkish baths are the direct and only descendant of the Roman baths of antiquity (Özguler and Kasap, 1999). Some of them are used even today in Turkey and in the countries of the former Ottoman Empire, e.g. Bulgaria, and Hungary. They are examples of precious historical places and objects.

FIGURE 1.5: Larderello, Italy – general view. Round building on the left hosts a geothermal museum. In the background, a geothermal power station facility (photo B. Kepinska)

FIGURE 1.6: Pamukkale, Turkey – famous travertine terraces formed by calcite precipitation from geothermal water (photo Z. Malolepszy)

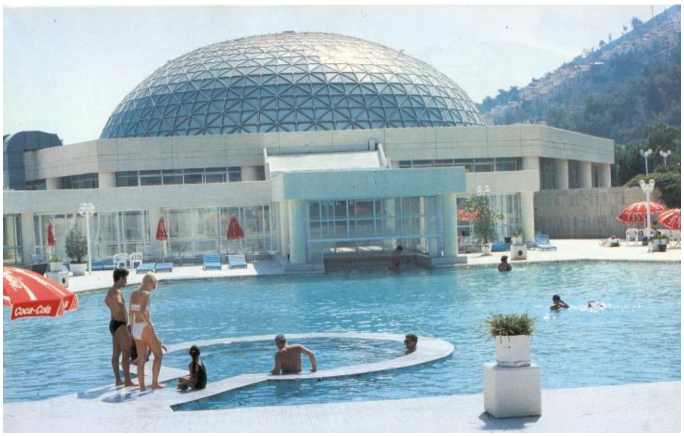

FIGURE 1.7: Izmir Balcova, Turkey – contemporary geothermal spa (photo S. Simsek)

The most important and renowned antique geothermal worship and healing places is Hierapolis (now Pamukkale) and Asclepieion in Pergamon. They are considered to be natural wonders attracting most of the tourists coming to Turkey. "Pammukale" means "cotton castle", owing to the white stalactites looming from water, and forming a huge stronghold. It was made of calcium carbonate, precipitating as a secondary hydrothermal mineral from warm springs. Water runs down from the plateau at 100 m of height through a system of terrace ponds down the slope (Figure 1.6). It cools down and fills the upper and then the lower ponds (Özguler and Kasap, 1999). The ancient name for the place was Hierapolis – "sacred city", established in the 2nd century B.C. Ruins of temples, theatres and baths constructed by the Romans have remained until the present times. Thermal water was used for bathing but not only. Its unique qualities were such that wool and carpets dyed in it maintained the vividness of colours. Presently, Pamukkale belongs to the most commonly visited places for landscape and therapeutic advantages. About 5 km from Pamukkale, a therapeutic centre in Karahayit was established. It abounds in geothermal water springs, as well as thermomineral red iron muds.

Asclepieion in Pergamon is known for Hellenistic culture and architecture. It was established for rite and healing purposes. This most beautiful and big city of ancient Greece was an example of a political and cultural leader in the Hellenistic world. Pergamon had its own "sacral-healing centre" – Asclepieion, built as a place of worship and cult of Asclepios, a Greek god of medicine. A system of temples and other objects were built in the place of occurrence of radioactive geothermal springs. The oldest temple dates back to the 4th century B.C. The architectural layout of Asclepieion was monumental in character, with an 800 m colonnade "sacred passage" leading from the city. The Greek priests, physicists, and philosophers developed a school of healing in Pergamon, which can be called the first and best example of organized natural healing and physiotherapy. Special care was taken to restore the health in its physical and spiritual aspects. A combination of treatments were applied there. Among the most fundamental ones were hot waters and herbs. Patients were treated by baths in geothermal waters, drinking of thermal waters, irrigations, massages, herbal therapies, diets, fasts, therapy through dreaming, autosuggestion, guided suggestion, and music. Many of the pools and bathing facilities in Asclepieion were filled with water from the local warm springs. Water was not transported to further distances as, according to the local beliefs, it could lose its therapeutic properties. The Pergamon area is known for its geothermal springs even today.

Apart from the heating industry, bathing and balneotherapy are the main geothermal direct uses in Turkey nowadays (Batik et al., 2000; Table 1.1) as the former contributes to over 47% of installed power and 27% used heat) while the latter 40% and 65%, respectively.

TABLE 1.1: Geothermal direct utilization in Turkey, 1999 (according to Batik et al., 2000)

| **Application** | **Installed capacity** | | **Heat production** | |
|---|---|---|---|---|
| | **($MW_t$)** | **(%)** | **(TJ/a)** | **(%)** |
| Space heating | 392 | 47.8 | 4,327 | 27.5 |
| Greenhouses | 101 | 12.3 | 115 | 7.1 |
| Bathing and balneotherapy | 327 | 39.9 | 10,314 | 65.4 |
| TOTAL | 820 | 100.0 | 15,756 | 100.0 |

There are about 1,000 geothermal springs and 194 geothermal spas in Turkey now (Batik et al., 2000). In a number of centres, cascaded use of geothermal waters is applied for heating, bathing and healing treatments. Baths of varying standards can be found in most Turkish cities where water from springs or geothermal wells is employed. The biggest and best known spa is Izmir Balcova (Figure 1.7). According to the plans of geothermal development, by 2020 the use of geothermal waters for heating purposes will be increased. A significant development of medicine based on geothermal waters is planned in the coming years to a level of 2,300 $MW_t$ from 327 $MW_t$ installed power in 1999, mainly to satisfy the Turkish demand.

## 4. GEOTHERMAL ENERGY IN CONTEMPORARY BALNEOTHERAPEUTICS AND TOURISM

### 4.1 Statistics

According to the data presented at the World Geothermal Congress 2000 in Japan (Lund and Freeston, 2000), direct geothermal uses were operational in at least 60 countries. The biggest share of installed power and heat production can be attributed to the heating industry and heat pumps. Geothermal energy used for bathing and swimming occupied the third place (Table 1.2). In many countries, bathing and swimming are important and attractive aspects of geothermal direct uses. Geothermal is utilized in this way in at least 51 countries, i.e. over 11% of total installed power and 22% of thermal energy for direct uses worldwide.

Nowadays, recreation and healing based on geothermal water, steam, and energy are a very attractive and perspective branch of tourism where the demand exceeds the supplies. Geothermal plays a number of functions in tourism, e.g. swimming and therapeutic pools, curative geothermal by-products (e.g. salts), ecological heating of hotels and spas. Hydrothermal phenomena themselves (warm springs, geysers, hydrothermal minerals, etc.) are tourist attractions, similar to the historical objects or ruins related with geothermal use. Incorporation of these phenomena and objects in the common domain of tourism favours the idea of "sustainable development" and pro-ecological development of many regions and countries.

TABLE 1.2: Geothermal direct utilization world-wide, 2000 (according to Lund and Freeston, 2000)

| Application | Installed capacity (MWt) | Installed capacity (%) | Heat production (TJ/a) | Heat production (%) |
|---|---|---|---|---|
| Heat pumps | 6,849 | 42.25 | 23,214 | 14.33 |
| Space heating | 4,954 | 30.56 | 59,696 | 36.85 |
| Greenhouses | 1,371 | 8.46 | 19,035 | 11.75 |
| Aquaculture | 525 | 3.24 | 10,757 | 6.64 |
| Drying of farm products | 69 | 0.43 | 954 | 0.59 |
| Industrial application | 494 | 3.05 | 10,536 | 6.50 |
| Bathing and balneotherapy | 1,796 | 11.08 | 35,892 | 22.15 |
| Air conditioning and snow melting | 108 | 0.67 | 968 | 0.60 |
| Other | 43 | 0.27 | 957 | 0.59 |
| TOTAL | 16,209 | 100.00 | 162,009 | 100.00 |

### 4.2 Healing and therapeutic value of geothermal waters

Generally, cold mineral and geothermal waters can be treated as "therapeutic" or "having healing properties" if they meet at least one of the following criteria: 1) chemical (chemical composition); and 2) physical (temperature, radioactivity). Both these criteria are met by geothermal waters which can, owing to their physical (over 20°C) and chemical properties, naturally play healing or therapeutic functions.

Temperature is one of the main factors thanks to which geothermal waters (just like regular mineral waters heated to a proper temperature) are applicable to healing, rehabilitation, and prophylaxy of diseases and dysfunctions of muscles, rheumatism, neurological diseases and many other ailments. Chemical composition greatly determines the application of geothermal waters for a spectrum of skin and internal diseases.

Individual countries have their own legal regulations and criteria for therapeutic waters and their applicability. For instance, in Poland, according to the Geological and Mining Law (1994), natural mineral waters or weakly mineralized waters (from 1 g/dm$^3$) are called therapeutic, if they are used for drinking treatments, baths, or inhalations. They are also used for the production of therapeutic salt, leaches and evaporated salt. The total dissolved solids of such waters cannot exceed 60 g/dm$^3$ and pharmacological-dynamic factors are taken into account. These minimum concentrations of chemical components dissolved in water or physical properties of water make up a threshold for biologically active waters. As an example, Table 1.3 lists pharmacological-dynamic coefficients that are used in Poland. Therapeutic waters cannot be contaminated with bacteria or chemical compounds. Their curative properties must be proven by tests, and the oscillations in chemical composition and physical properties of waters may change only in a very small range.

### 4.3 Therapeutic tourism

Geothermal balneotherapy and spas are basic elements of therapeutic tourism, one of the most important forms of recreation nowadays. Healing purposes can be acquired through various forms of tourism (spas, weekend tours, general healing tours, healing tours dedicated to specific diseases, etc.) Today, therapy is one of the fundamental functions of tourism, thanks to which the negative effects of civilization, e.g. stress can be reduced, and the inner force and feeling of integration reinforced (Gaworecki, 1997). Over the centuries, these purposes have been most successfully realized in health resorts, i.e. spas, especially those with geothermal water. Spas are also attributed to a specific lifestyle, leisure, healing and biological rejuvenation, an aspect of cultural and social life.

TABLE 1.3: Pharmacological-dynamic coefficients and relevant names of therapeutic waters used in Poland (based on Dowgiallo et al., 1969)

| Content in 1 $dm^3$ of water, more than | Type of water |
|---|---|
| 10 mg $Fe_2^+ + Fe_3^+$ | Ferruginous |
| 0.7 mg As in the form of $AsO_2^-$ (1 mg) or $HAsO_4^-$ (1.3 mg) | Arsenic |
| 1 mg $F^-$ | Fluoride |
| 5 mg $Br^-$ | Bromide |
| 1 mg $J^-$ | Iodine |
| 1 mg S – determined iodometrically ($H_2S + HS^- + S^{2-} + S_2O_3^{2-} + HSO_3^- + HS_3^-$) | Sulphide |
| 5 mg $HBO_3$ | Boride |
| 100 mg of dissolved $SiO_2$ | Siliceous |
| 1000 mg dissolved natural $CO_2$ | Carbonated |
| $2x10^{-9}$ Ci (2 nCi, 74 Bq) | Radon-active |
| Temperature of water at the outlet, ≥ 20°C | Thermal |

The word ‘spa’ was used for denoting places where balneotherapy had been used since the times of ancient Greece and Rome (Section 3). Over the centuries, it gained new connotations, i.e. in 19th Century Europe ‘spa’ was also a social and cultural centre, frequented by noble and rich people. Even today, apart from strictly curative functions (under supervision of physicians and specialists), the cultural and social aspects became very important in Europe. In the U.S.A., however, spas are mainly centres with a variety of accompanying treatments including fitness, rejuvenation, weight-loss, sport programs, and curing in mineral waters and thermomineral muds. Contemporary spas should offer: water (therapeutics through heat and chemicals); movements (exercise, massage, and fitness); herbal; dietary; and life-style patterns (Lund, 2001a). Another significant aspect is the attractive landscape and climate in the spa. They may considerably add to the efficiency of therapy. Therefore, apart from water, there are also spa muds (peloids) which are an important therapeutic medium. Their use increases body temperature, lowers blood pressure, and influences mineral metabolism and blood chemistry. It should be remembered that different assumptions are made for spas in the U.S.A. and Europe and are different for such countries as, e.g. Japan, which employs its own tradition and philosophy of life in harmony with nature.

## 4.4 Geothermal energy in tourism, therapy and recreation – selected cases

### 4.4.1 Geothermal spas in Hungary

Hungary abounds in rich geothermal resources in the large Pannonian Basin (Tertiary - Neogene), its Mesozoic basement as well as Tertiary and Quaternary volcanites. In 1999, the installed power for direct uses was 342.6 $MW_t$, and heat production 3182.5 TJ/year (Arpasi et al., 2000; Lund, 2000). Geothermal energy has been used on a great scale for greenhouses (over 60% of installed power and 56% of heat production), giving Hungary the world’s first place in the coverage of geothermally heated greenhouse cultures. Among other direct applications in Hungary are central heating, industrial applications, swimming pools and balneotherapy; the latter constitutes about 13% of other applications (Table 1.4).

Bathing places and spas employing geothermal waters belong to the biggest tourist attractions of Hungary, which is a leader in Europe and in the world. Geothermal traditions date back to the Roman Empire, when a demarcation line between the northernmost part of the Empire came through this area. The Turks had also their impact in the application of hot waters. They built large baths and objects for recreation and biological rejuvenation. Most of these centres are in Budapest, the capital of Hungary.

Geothermal waters, similar to mineral waters of Hungary, vary in chemical composition, thus creating a number of possibilities for therapy.

TABLE 1.4: Geothermal direct utilization in Hungary, 1999
(based on Arpasi et al., 2000; Lund, 2000)

| Application | Installed capacity | | Heat production | |
|---|---|---|---|---|
| | ($MW_t$) | (%) | (TJ/a) | (%) |
| Space heating | 73.1 | 21.3 | 631.6 | 19.8 |
| Greenhouses | 206.7 | 60.3 | 1785.8 | 56.1 |
| Industrial applications | 14.2 | 4.1 | 358.2 | 11.2 |
| Bathing and balneotherapy | 44.8 | 13.2 | 386.7 | 12.3 |
| Heat pumps | 3.8 | 1.1 | 20.2 | 0.6 |
| TOTAL | 342.6 | 100 | 3182.5 | 100 |

Hungarian geothermal spas and baths are a strategic tourist attraction, known all over the world. In international touristic campaigns, Hungary is recommended as "a country of healing waters" while Budapest is called a "capital of bathing and swimming". Geothermal baths, being one of the greatest attractions in Hungary, are offered by a number of foreign travel agencies. Some of them specialize in therapeutic tours to Hungary. They offer their biggest and best organized geothermal spas, e.g. in Budapest and Heviz – two renowned places.

**Budapest.** Budapest was formerly known as Ak - ink. In Celtic, it signified abundance of water, one of many natural goods. Aquincum – the Roman camp and baths were built by Emperor Claudius (260 to 268 A.D.). Roman emperors - Mark Aurelius and Traian stayed in Budapest, enjoying curative properties of hot springs. The Romans constructed a system of aqueducts supplying water for the city and baths. At the beginning of Hungary in 896, water from Aquincum springs was transported through a 10 km timber pipeline to the castle of Buda. Remnants of Aquincum are one of the greatest archaeological and tourist attractions of Budapest (Cohut and Arpasi, 1999).

Another stage of geothermal spring applications in Budapest is related with the times of Ottoman Turkey. In the 16$^{th}$ to 17$^{th}$ century, they constructed numerous baths (*ilidse*). *Ilidse* were very spacious and they could house thousands of people daily. The most renowned Hungarian *ilidse* were constructed by Mustafa Sokoli – Pasha in 1566. It is worth noting that baths were sited near warm springs, so that the visitors could use them directly. They wanted to avoid transportation of water over great distances (as the Romans did using their aqueducts). Such popular and attended baths as Rudas and Király were constructed in Ottoman times. Five pools for therapeutic and recreational purposes have been preserved in Rudas baths. Nowadays, geothermal waters are used in a number of treatments, including drinking therapy.

In the times of a great advance in medicine, healing with geothermal waters started to flourish in Hungary in the second half of the 19$^{th}$ century. At that time, Budapest was one of the most popular metropolises in the whole of Europe. Since the Millennium of Hungary in 1896, Budapest started to bloom as the capital city and centre where such natural goods as geothermal springs were used. A few more baths were constructed at that time. They are operational today. At present, the citizens of Budapest (2.1 million) use about 130 springs and geothermal intakes. Geothermal baths in Budapest can be divided into: therapeutic baths, all kinds of recreation swimming pools (open all year long), and seasonal recreation swimming pools (Wolski, 1988).

Budapest is one of the biggest geothermal bath-cities in Europe. It very much resembles Reykjavik – the capital of Iceland, known for numerous bathing and swimming centres operating on geothermal waters. In 1934, Budapest was put among resorts. This city fully employs its natural geothermal wealth in about 40 baths, pools, and therapeutic centres. Each of them has a different architectural layout. Among the most beautiful and at the same time very functional ones are objects built in Secession, Neo-baroque, and Classicist style. A number of these precious historical objects, often over 400 years old (!), are still used as Turkish baths. All geothermal objects have been so designed as to attract the patients to revisit the place. The Gellert Hotel, sited on a steep slope of the Danube River, is such a place where apart from regular hotel services it also offers a variety of therapeutic treatments in gorgeous Secession interiors (Figure 1.8). A great number of such centres in Budapest itself intensify their promotion policy to invite as many foreign tourists as possible. Thus, apart from its various attractions, Budapest allures people coming from abroad with its geothermal leisure and therapy centres.

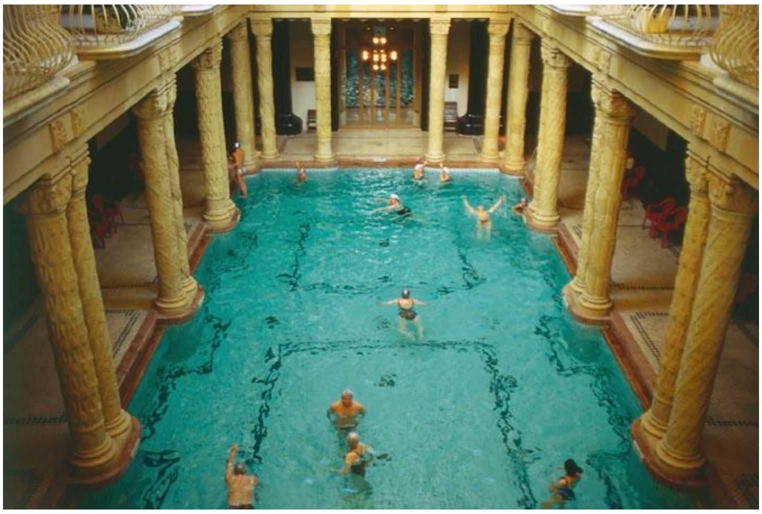

FIGURE 1.8: Budapest, Hungary – geothermal indoor pool in Gellert Hotel and Spa (www.budapest.info.hungary)

**Heviz.** Heviz resort is sited near the Balaton Lake – the so-called "Hungarian Sea". Heviz is known for its unique (the biggest in continental Europe) warm lake fed with spring waters at 38-40°C. Therefore, it slightly reminds of Myvatn Lake in Iceland, which is supplied by hot springs, too. The Heviz Lake covers ca. 48,000 m² (Figure 1.9). Springs have been active since the Tertiary times, and the hot waters were used for bathing in the Bronze Age when the Romans had restructured them to a spa (Cohut and Arpasi, 1999).

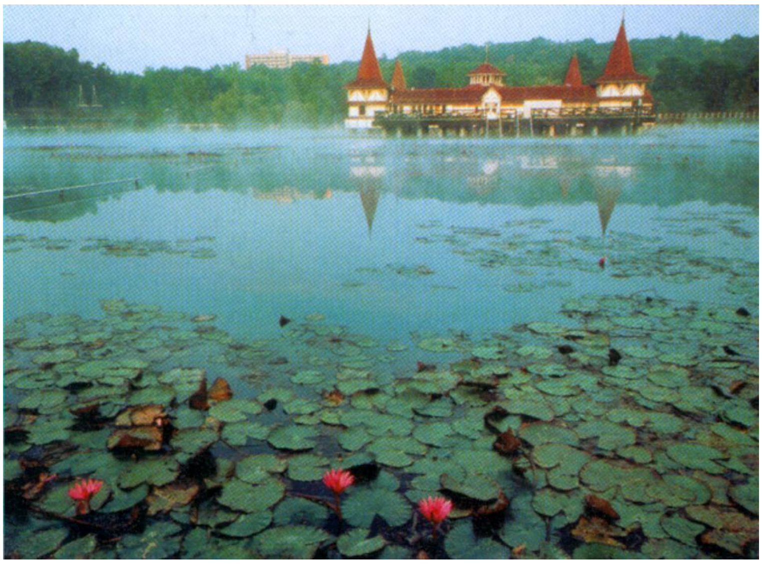

FIGURE 1.9: Heviz resort, Hungary – a lake recharged by geothermal springs (www. hungarytourism.hu)

Water temperature in the lake is 26-28°C, thanks to which this naturally warm pool can be used all year long. The mud in its bottom has curative properties and is used for treatments. The banks of the lake are grown with tropical vegetation, water lilies, and cypresses. Heviz offers both hotel services and the therapy treatments and tours. They are very attractive and versatile – from typically therapeutic to "cure and fitness".

It would be difficult to present all spas and resorts in Hungary with their rich offerings. It is worth noting that apart from big centres, there are plenty of smaller towns and localities. They are adjusted to the needs of local population and a smaller number of incoming tourists. They are usually equipped with basic utilities and infrastructure. Therapy, rehabilitation and tourism in Hungary are provided on the same level as their counterparts in Western Europe, however much cheaper. Therefore, no wonder that so many travel agencies offer "Cure and Fitness" tours in Hungary.

### 4.4.2 Japan - tradition and advances in geothermal tourism

Japan has about 200 volcanoes, out of which ca. 80 are active now. Besides, Japan abounds in rich reserves of geothermal steam and water. They are used both for electrical energy generation and many other direct uses, which place Japan in second place in the World (Lund and Freeston, 2000). These are, e.g. recreation and balneotherapy – both having a very long and interesting history (Section 3).

The present situation in direct geothermal uses can be characterised by data of 1999 (Sekioka and Yoshii, 2000), according to which the installed capacity for these applications was 270.40 $MW_t$, and heat production 5455.2 TJ/year. Geothermal energy is mainly used for space heating and warm useful water production (over 50% of installed power and heat production), then for greenhouses (over 12% of power and heat) as well as for recreation and balneotherapy (over 10% of installed power and heat production); see Table 1.5).

TABLE 1.5: Geothermal direct utilization in Japan, 1999 (Sekioka and Yoshii, 2000)

| Application | Installed capacity | | Heat production | |
|---|---|---|---|---|
| | ($MW_t$) | (%) | (TJ/a) | (%) |
| Space heating | 136.71 | 50.6 | 2953.32 | 54.2 |
| Air conditioning | 5.43 | 2.0 | 58.50 | 1.1 |
| Greenhouses | 34.59 | 12.8 | 653.77 | 12.0 |
| Fish farming | 23.76 | 8.8 | 576.99 | 10.5 |
| Industrial applications | 2.12 | 0.8 | 42.78 | 0.8 |
| Snow melting | 31.85 | 11.8 | 494.71 | 9.1 |
| Bathing and balneotherapy* | 28.89 | 10.7 | 551.83 | 10.1 |
| Other | 2.78 | 1.0 | 67.74 | 1.2 |
| Heat pumps | 4.28 | 1.5 | 55.57 | 1.0 |
| TOTAL | 270.40 | 100 | 5455.20 | 100 |

* List of geothermal applications for bathing and balneotherapy is not complete (see the text)

As to the use of geothermal steams and waters in recreation and therapy, the data listed in Table 1.5 do not reflect the actual scale. Paradoxically, this is due to the huge number of places where geothermal utilities are operational. Japanese statistical offices fail to make a reliable inventory of these places. Japanese treat baths and leisure in geothermal utilities as a very popular and common way of spending time. This is a part of Japanese rites, culture, and lifestyle; therefore they pay no attention to evidencing geothermal objects, especially the low-temperature ones. Taking into account springs and wells used for recreation and therapy, the installed power and geothermal heat production is about 1,159 MWt and 7,500 TJ/year, respectively. Balneotherapy, biological renovation, and recreation occupy the first place among direct uses of geothermal energy in Japan and in other countries all over the World (Lund and Freeston, 2000).

Tourism in Japan is closely connected with geothermal, hydrodynamic, and volcanic phenomena, e.g. Fuji, which is a sacred mountain, a symbol of the country and place where numerous pilgrimages come. Japan has specific legal regulations known as “Hot Springs Law” addressing the protection of springs, other geothermal phenomena, and landscape. It forbids or limits their practical exploitation in places considered to be especially valuable geologically or environmentally.

Japanese national parks are a great attraction. Geysers, hot springs, and volcanoes are protected in 15 out of 24 of the parks. Attention should be paid to the promotion of these places and good information abounds in interesting details on geology and geothermal.

FIGURE 1.10: Beppu, Japan –„Jigoku Park”. An example of joining the traditional and contemporary touristic arrangement of a geothermal area. A figure of the devil – believed to be a guard of geothermal manifestations, and a table explaining the origin and composition of hot springs (photo B. Kepinska)

Tourism started to grow around hot springs and hydrothermal manifestations, e.g. Beppu on Kyushiu – the venue of the first part of the World Geothermal Congress 2000 in Japan. It is known for the abundance of natural steams and geothermal springs, and also the first Japanese experiments on the use of geothermal steams for electrical energy generation. Beppu is a big (ca. 400,000 population), frequented and well organized resort. There are a number of hotels of varying standards, offering the whole spectrum of treatments and therapies based on traditional Japanese medicine, employing geothermal waters, thermomineral muds, and hydrothermal minerals. In Beppu, just like in other cities in Japan, many of the hotels were designed especially for rejuvenation and curative purposes in the place where geothermal springs occur. These hotels are called “onsen” (no counterpart in other languages).

A special tourist attraction, Beppu, is sited on the slope of the volcano, an area of hot springs, geysers, fumaroles and hot muds. It is called the burning hell – “Jigoku”. This area is protected and popularized by a special Association of Jigoku in Beppu. Water in individual springs and ponds differ in colour, depending on the chemical composition and temperature, from emerald, red, milky white to green. Specific places bear meaningful names, e.g. “Sea Hell”, “Mountain Hell”, “White Pond Hell, “Golden Dragon Hell, and “Blood Hell”. They are linked by a few kilometre long tourist route. A number of small temples and meditation spots were elected around the springs and ponds. A new tourist infrastructure was created with information centres, restaurants, shops with souvenirs, e.g. therapeutic salt or table salt extracted from local springs, and clothes dyed in paints made of local hydrothermal minerals (Figure 1.10). Among other attractions are a zoo, tropical garden, and before all, a crocodile and alligator farm, bred in geothermally-heated pools. The farm can be entered through the shop offering products made of crocodile skin and meat, i.e. jewellery, leather products, medicines, ointments, and food products. In “Jigoku”, the visitors have a chance to buy food cooked in “geothermal ovens”, simple devices heated by natural steam or bamboo or metal nets hung over the steaming ponds (Figure 1.11).

FIGURE 1.11: Beppu, Japan – “Jigoku Park”. One of the natural ponds fed by hot springs. A basket with eggs is submerged in steaming water. When cooked, the eggs are sold as “geothermal food” (photo B. Kepinska)

Geothermal waters are also used for gardening. Japan is famous for its art of growing plants and use geothermal water for greenhouses where exotic plants are grown. Geothermal energy is used for heating greenhouses with exotic species, and watering plants which are an important element of famous Japanese gardens.

### 4.4.3 Bulgaria

Bulgaria is very fortunate to have a variety of cold and geothermal mineral waters. They are issued by thousands of natural springs, including more than 500 geothermal (Bojadgieva et al., 2001). Waters with high alkalinity, low levels of TDS, and high purity are predominant. These features place them among the best ones in Europe regarding their use for recreational and therapeutic purposes. Bulgaria is a very attractive country for European tourists because of its healing and recreational possibilities. The tourist offerings are exceptionally alluring owing to an extraordinary combination of such factors as: abundance of geothermal waters and the traditions of their use for treatment, mild Mediterranean to moderate climate, variety of landscapes (sea, mountains), rich folk culture, and customs.

In 1999, the installed capacity for geothermal direct uses was 95.3 $MW_t$ (Bojadgieva et al., 2000). Geothermal energy has been implemented on a large scale for balneotherapy and bathing (46.4% of total geothermal water flowrate), followed by space heating (20.3%), sanitary water preparation (14.8%), greenhouses (10%), and water bottling (5.1%).

The tradition of geothermal bathing and balneotherapy in Bulgaria dates back to the ancient times. A number of large spa resorts have developed in places of Thracian or Roman residential areas (Figure 1.12). Also Sofia - the capital city, was established close to geothermal springs in the 3rd century B.C. (Bojadgieva et al., 2001).

There are many spas using geothermal waters suitable for disease prevention, treatment, and rehabilitation of many illnesses. They are used for drinking, bathing, inhalations, in combination with herbs, bee products, climatherapy, aromatherapy, and exercise.

A unique combination of sea resorts and geothermal spa centres can be met in the North Black Sea region. Geothermal springs and pools are located very close to the seashore or even directly at the beaches. Geothermal pools are also placed there. Among the best known modern resorts located there are Varna, the Golden Sands, Albena (Figure 1.13), St. Constantin and Elena. They provide a very attractive combination of seawater baths with geothermal water and mud baths. In several resorts, geothermal energy is also used in a complex way, i.e. for heating, air conditioning, and warm water preparation for balneotherapeutical complexes, sanatoriums, public baths, etc.

Balneotherapy has reached a very high level in Bulgaria. The same can be said about the medical level and efficiency of treatment. In this country, there are good prospects to develop geothermal recreation and balneotherapy not only in big centres but also small local ones in line with the trends of “the countryside tourism”, similar to several other European countries, for instance Poland or Slovakia.

It is worth noting that Bulgaria specializes in microalgae cultivation using geothermal energy, water, and carbon dioxide (Figure 1.14). This provides high process optimization and considerably reduces the production costs (Fournadzhieva et al., 2003). Microalgae biomass is produced from three species of microalgae: Chlorella, Scenedemus, and Spirulina. It is a natural material rich in biologically active and harmless substances for the pharmaceutical, cosmetics, and food industries. It has a very high protein content, rich mineral content, vitamins, antioxidants, essential fatty acids and polysaccharides. They are used for stimulation of the immune system, support for the cardio-vascular system, reducing the risk of cancer, etc. Microalgae biomass is available at the market in the form of tablets or cosmetics. In this field, Bulgaria is a leading country in Europe, along with Greece.

FIGURE 1.12: Hisarja resort, Bulgaria – geothermal water fountain. Hisarja is one of the largest spas in Bulgaria known since the ancient times (photo K. Bojadgieva)

FIGURE 1.13: Albena resort, Bulgaria – outdoor geothermal pool placed close to the Black Sea coast (photo K. Bojadgieva)

FIGURE 1.14: Rupite region, Bulgaria – open mass cultivation of microalgae using geothermal water and energy (photo K. Bojadgieva)

### 4.4.4 Poland

#### 4.4.4.1 General remarks

Poland possesses rich low-enthalpy geothermal resources predominantly connected with extensive sedimentary formations (Sokolowski, 1993; Sokolowski [ed],1995; Górecki [ed], 1995). Although this country has a long tradition in geothermal bathing and healing, dating back to the 13th century, it is also involved in the process of geothermal heating implementation, started in the end of the 1980s. The latter line of uses is treated in detail in Lecture 3. In 2003, the total installed power amounts to 108.2 $MW_t$, and heat production 455.5 TJ/a (Kepinska, 2003). Geothermal is primarily used for heating and domestic warm water preparation (72.3% of installed power and 73.7% of produced energy) while balneotherapy and bathing occupy the second position (17.3% and 7.6%, respectively; Table 1.6).

In Poland, there are 36 spas applying underground waters for balneology and bathing. Among them, seven spas use 20-62°C geothermal waters delivered by natural springs or discharged by wells. Although not too numerous, geothermal spas offering curative and recreational services are an important element of health resorts in Poland.

The first written records report that since the 13$^{th}$ century, warm spring waters have been used for balneotherapy in some localities. Yet undergoing up- and down-periods, this practise developed much in time, to the point that some stations became quite renowned spas in Central Europe. With time, several other spas using geothermal waters have been founded and they are still in operation (Sokolowski et al., 1999).

Polish spas (also geothermal ones) act according to legal regulations on spas and balneology, adopted in 1966 and amended in 1990. The spa localities hope for prosperous, sustainable economic development resulting from recreation and balneology. It is expressed by establishing many so-called spa boroughs within the entire country. The development of balneology and spa services in Poland require support by the state and self-governments. Among others, the Economic Chamber – Polish Spas was created for that purpose. It gathers companies and institutions dealing in spas. Its main objective is representing spas' interests against home and foreign bodies, acting for the development of the existing spas and establishing new ones, participation in legislative works, promotion, and the elaboration of the spa standards. The role of the local self-government in spa management, as well as the other activities serving the sustainable development of such localities should be emphasised.

TABLE 1.6: Poland – summary of geothermal direct uses, early 2003 (Kepinska, 2003)

| Type of use | Installed capacity | | Heat production | |
|---|---|---|---|---|
| | ($MW_t$) | (%) | (TJ/a) | (%) |
| Space heating and domestic warm water | 78.2 | 72.3 | 336.0 | 73.7 |
| Balneotherapy and bathing | 18.7 | 17.3 | 34.5 | 7.6 |
| Greenhouses, fish farming, drying | 1.0 | 0.9 | 4.0 | 0.9 |
| Other – extraction of CO2 and salts | 0.3 | 0.3 | 1.0 | 0.2 |
| Heat pumps (estimated) | 10.0 | 9.2 | 80.0 | 17.6 |
| TOTAL | 108.2 | 100 | 455.5 | 100 |

#### 4.4.4.2 Geothermal spas – a review

To give insight into geothermal spas in Poland, a selection of cases is presented in this chapter. Each of them has its own interesting history distinguishing it from other ones. The oldest spas in Poland are located in the Sudetes Mts. (SW-Poland). Abundant mineral springs have been used there for healing purposes. Some of them produce geothermal water that has greatly contributed to the development of certain resorts, e.g. Cieplice Spa, Ladek Spa, and Duszniki Spa. Warm waters are connected with fractured Pre-Cambrian and Palaeozoic metamorphic or magmatic formations. The convenient location of these resorts close to the frontier attracts patients and tourists from the neighbouring countries – Czech Republic and Germany. In the central part of the country, cold and geothermal waters connected with Mesozoic sedimentary formations and discharged by the wells are used for curing in Ciechocinek and Konstancin. Three resorts using geothermal waters are situated in the Carpathian Mts. (S-Poland): Iwonicz, Ustron and Zakopane. This region abounds in low-temperature mineral springs, which gave rise to numerous health resorts. However, warm waters are used only in three of them.

**Ladek Spa.** Ladek is the oldest spa resort in Poland. The first records of warm waters come from 1242. The first bathing house was built at the end of the 15$^{th}$ century. Among numerous visitors who stayed at Ladek for curing, was John Quincy Adams, the sixth President of the United States of America (1825-1829). At the end of his visit in Ladek he said: "I have never seen a spa, the location and appearance of which would be as much favourable to health preservation and restoring as Ladek" (Sokolowski et al., 1999). These words have remained the best advertisement of this spa so far.

Radioactive waters with temperatures of 20-44°C and rich in fluorine ion F (up to 11 mg/l) and $HSiO_3$ (up 70 mg/l) produced by several springs and wells are suitable mainly for treating patients with the motor system, vascular, oral and dermatological diseases. Among Polish resorts, Ladek Spa possesses one of the greatest therapeutic bases (Figure 1.15). Wide promotion and advertising of the spa, also addressing foreign clients, especially from the nearby Czech Republic and Germany are conducted. The cultural performances are organised and sponsored. A system of preferences and discounts was introduced. Some interesting offers for investors were prepared. Ladek is a good example of a spa town which offers not only curing services, but also a variety of rest, health preventive treatment, and physical recovery possibilities.

**Cieplice Spa.** Cieplice is one of the most famous and visited spas in Poland. The oldest historical record of Cieplice comes from 1281 when warm springs were already applied for curing (Sokolowski et al., 1999). The spa of European fame already operated in the 17-19$^{th}$ centuries. Currently, the water flows out from several natural springs (ca. 20-44°C) and from one well (wellhead temperature of 60-68°C, TDS ca. 600-1000 mg/l). The content of $H_2SiO_3$ amounts to 100 mg/l and is the highest among all geothermal waters in Poland, very high is also the content of fluorine ion – up to 12 mg/l (Dowgiallo, 1976; Dowgiallo and Fistek, 1998).

FIGURE 1.15: Ladek Spa, Poland – balneotherapeutics station "Wojciech" using geothermal water for healing treatment. Built in the 17$^{th}$ century in Baroque style (photo L. Zimer – Skarbinska)

In past centuries, the most magnificent patient who visited Cieplice was the Polish queen Maria d'Arquien Sobieska who came there in 1687. The queen was accompanied by about 1,500 people of court. She was the beloved wife of one of the greatest Polish kings Ian III Sobieski whose army stopped the Turkish invasion in Europe in the famous battle of Vienna in 1683. Two of the warm springs in Cieplice were named after King Sobieski and his wife.

FIGURE 1.16: Cieplice Spa, Poland – one of the indoor curative geothermal pools (photo L. Zimmer – Skarbinska)

In the end of the 1990s, the other existing well in Cieplice was deepened from 661 m to 2,002 m. The self-outflow of ca. 90 m$^3$/h water with a wellhead temperature of 87.9°C was obtained (Dowgiallo, 2000). Those works were carried out in response to the growing demand for curative water, planned sport and recreational facilities, and the project of utilisation of the water for space heating purposes (Figure 1.16).

**Duszniki Spa.** The first records on warm springs from Duszniki come from 1408. Currently, geothermal waters are produced under artesian conditions from several shallow (up to 160 m) wells and one spring. The wellhead temperatures are 17-18°C. These relatively low temperatures result from the fact that waters are cooled down on the way to the surface due to expansion of dissolved $CO_2$ (Dowgiallo, 1976).

Duszniki Spa is famous thanks to Fryderyk Chopin - the great Polish composer and pianist (1810-1849) who stayed there for a healing treatment in 1826. He was only sixteen when he came to the resort along with his mother and sister. During his stay in Duszniki, the young artist gave one of his first public concerts raising sincere admiration of the audience. This was one of the first performances,

FIGURE 1.17: Duszniki Spa, Poland – warm spring named "Pieniawa Chopina" (the Spring of Chopin) (source: www.duszniki.pl)

which opened the gateway to the world's artistic career to Chopin (Sokolowski et al., 1999). To commemorate the artist's genius and his stay in Duszniki, the warm spring was given the name "Pieniawa Chopina" (the Spring of Chopin; Figure 1.17). Each year, the Chopin international music festival is organised, where outstanding musicians and numerous international audiences come. The spa conducts a wide policy of its development, namely: expansion and modernisation of recreation and tourism infrastructure, sustainable development, Chopin Festival of Music, promotion and advertising, co-operation with other spas in this region, joint promotion of the curing advantages, and offers for investors.

**Ciechocinek.** Ciechocinek spa (Central Poland) started to operate, making use of cold therapeutic brines. In the first half of the $19^{th}$ century, the spa started its "geothermal" stage of development when the first "warm water" wells were drilled. At present, both cold and warm waters are used in Ciechocinek for therapeutic purposes. Geothermal aquifers are found in the Jurassic sandstones. Currently, the spa is supplied with cold and geothermal water, discharged by several wells. 29-37°C waters are produced by two wells (ca. 1300 m and 1380 m depth). The TDS varies from 3 to 72 g/l depending on the depth of the aquifer. Waters predominantly represent Cl – Na + F + Br + J +B + ($SO_4$ + $H_2S$) type (Krawiec, 1999). The iodine and bromine content is generated by the extensive Zechstein salt formations. The salt minerals are dissolved by waters of probably paleoinfiltration meteoric origin. Along with exploitation of water for curing and bathing purposes, the table salt (with iodine content), some kinds of mineral waters, lye and crystalline slime have been produced as well.

The development of the town and its neighbourhood commenced after the first partition of Poland in 1772 when the central part of Poland lost its access to the Wieliczka salt mine. At that time, brine sources for salt extraction were sought (Sokolowski et al., 1999). In 1836, the saline springs started to be used also for healing purposes. From 1841-1860, the first shallow wells were drilled. They discharged warm brines with temperatures in the range of 18°C. According to the project of Stanislaw Staszic – the pioneer of Polish geology and mining - specific wooden installations (2.5 km long) were built, referred to as the graduating towers, and used for spraying iodine-bromine brines. In such a way, an ocean-like microclimate was created, especially suitable for natural curative inhalations. These installations are still in use (Figure 1.18)

FIGURE 1.18: Ciechocinek Spa, Poland – one of the graduating towers spraying warm brine and creating an ocean-like microclimate (photo A.Krawiec)

At present, Ciechocinek is one of the main Polish resorts. The number of cured persons exceeds 30,000 per year. The following elements add up to the success and reputation of the spa:

- Variety and high quality of curing service;
- Production of curing means in a wide range;
- Spa facilities strictly satisfying the requirements of curing people;
- High quality and volume of the accommodation and catering base (19 sanatoriums, 8 spa hospitals, numerous lodging houses, restaurants etc.);
- Excellent urban layout of the spa – four spa parks, gardens, nature reserves;
- Wide promotion and advertisement.

**Iwonicz Spa.** Iwonicz Spa is located in the Carpathians. Geothermal brines (ca. 20°C) occur within the Eocene sandstones. They are currently produced by several post-extraction oil wells (to 1000 m depth). The TDS vary from ca. 8 to 20 g/l. The brines represent the type Cl - $HCO_3$ – Na + Br + J + ($CO_2$ + $H_2S$). Opposite to many other cases, geothermal waters of Iwonicz occur in specific geological-reservoir conditions, filling local traps in sandstones. Their reserves are non-renewable thus must be exploited with special care.

The first records of the use of warm springs in this locality date back to 1578 and 1630, when they were described by the royal physicians. In 1856, Jozef Dietel - professor of the Jagiellonian University, called Iwonicz a "prince of iodine waters" (Karwan, 1989). Iwonicz water was bottled and sent around Europe (!). The first wells (400-600 m deep), supporting the existing springs, were drilled at the end of the 19th century. With time, the former springs vanished, and exploitation started from the post-extraction oil wells (Sokolowski et al., 1999). Warm brine discharged by one of them has been used until now

Waters are used for drinking and bathing treatments (including peat baths), and also for curative and cosmetic salt extraction. The patients are also offered a number of therapeutic products. Apart from cold and warm waters, Iwonicz therapeutic salt is also used (its large-scale production started after 1918). In 1926, the peat bricks "Iwonka" (a mixture of dry forest peat and iodine-bromine salt and mud from salt factories) started to be extracted. Even now this kind of treatment is provided for compresses and post-accident rehabilitation treatments. Recently, a new line of hypoallergenic cosmetics based on the Iwonicz geothermal water was started. This is the first case in Poland where geothermal water has been used for cosmetics production.

Balneotherapy in Iwonicz is mainly based on local products which greatly adds to the success and popularity of the spa. It belongs to one of the best known and most frequented Polish resorts (over 30,000 patients and tourists per year).

**Zakopane and Podhale region.** Zakopane (S-Poland) is located at the foot of the Tatra Mts. (the highest part of the Carpathians). The Tatras, Zakopane and the Podhale region, constitute the main centre of tourism and winter sports in Poland. Over 3 million tourists visit this place each year. In the last few years, construction of a large-scale district heating system and other types of direct geothermal utilization started to be carried out there (see Lecture 4) including balneotherapy and bathing.

The tradition of using warm waters for bathing is connected with a 20°C natural spring. It was used by the local highlanders long before the middle of the 19$^{th}$ century. In the period between the 1970s and 2001, a small geothermal bathing centre was operating in Zakopane downtown. It used warm (26-36°C) waters from two wells (Figure 1.19). Construction works on a large geothermal spa and recreation centre started in 2001. This investment is financed from Polish and European Union sources. This is a long-awaited project, indispensable to broaden the offer of the city and to improve the quality of recreation for winter tourism in the Polish capital.

FIGURE 1.19: Zakopane, Poland – geothermal pools existing until 2001 (since 2001 construction of an aqua park) (photo M. Kowalski)

Over ten geothermal wells have been drilled within this area so far. They yield 20-87ºC waters which have curative properties suitable in many diseases. They create exceptionally great possibilities to build water centres in this region. In fact, every locality, where wells discharging geothermal waters appear, can have its own geothermal centre tailored to the needs of both the inhabitants and tourists. These can be both large and smaller centres fitted in local architecture and landscape, following the trend of 'countryside tourism'.

### 4.4.4.3 Some prospects for the future

In recent years, growth of interest in recreation and water centres development, as well as water therapeutics including geothermal water applications has been evident in Poland. This interest concerns the operational spas as well as – it's worth noticing – the localities in Central Poland which have never dealt in this field and which plan to develop that activity from the very beginning, using the geothermal waters discharged from existing or planned wells. In some cases, also the existing geothermal spas initiated the activities aimed at increasing the amount and quality of warm waters accessible for curing. It was done in two resorts in the Sudetes, where the existing wells were deepened and new ones were drilled.

In recent years, apart from projects for the comprehensive and multipurpose use of geothermal energy in Poland, there have appeared opportunities to develop new geothermal spas and water parks near the city agglomerations, where political, economical, and business centres exist. Such centres express great and constantly growing need for recreation, biological rejuvenation and treatment services. These facts are an important stimulus for the creation of new bathing facilities. Therefore, they should raise interest among investors and in the future also generate financial benefits. Although not fully understood and exploited, geothermal therapy and recreation are a promising line of business with great opportunities for development in Poland. One of the limitations of wide, adequate development is still insufficient promotion and funds.

Besides the already existing structures, there are plans to build new geothermal health and recreational spas. The popularity of the water centres, several of which have already been constructed (non-geothermal), raises the interest and gives a spur to build more such facilities, including geothermal. In general, the centres could be one of the elements of integrated or cascaded geothermal systems. They would be designed to use waters from deep and shallow wells, or thermal energy stored in shallow ground horizons, often with additional use of heat pumps and other renewables.

## 5. CLOSING REMARKS

Geothermal energy occupies a significant place in the development of human civilization, and also in the formation of various historical relations of man with Nature and its resources, their understanding and proper implementation. The author hopes that the presented cases and aspects will help to realize that geothermal belongs to such energy sources, or more broadly – natural resources, which have had a great positive impact on the development of material, spiritual and social culture of a number of countries. Over the centuries, man's relationship with geothermal has greatly improved the understanding, application and protection of geothermal. This kind of experience can also be extended to other natural energy sources. Nowadays, geothermal energy has much to offer to generate power and heat, for industry, and also for medicine, tourism and recreation. It is a great challenge and an amazing source of possibilities, thanks to which the idea of sustainable development can be realized.

"Geothermal energy for the benefit of people" – with these words numerous profits related with everyday use of geothermal energy are defined. If geothermal is applied for recreation and therapy, these words seem to be particularly adequate to represent the actual positive influence of this kind of energy on the physical and spiritual condition of man.

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# LECTURE 2

# GEOTHERMAL ENERGY DEVELOPMENT IN EUROPE – AN INSIGHT INTO CURRENT METHODS AND TRENDS

## 1. INTRODUCTION

Europe belongs to the world's leaders in geothermal direct uses. It occupies the second place after Asia, and before the Americas, Africa and Oceania. According to the data presented at the World Geothermal Congress 2000 in Japan (Lund and Freeston, 2000), geothermal energy is directly used in 28 European countries (for a total of over 60 countries reporting this type of use). Geothermal resources in Europe represent primarily low-enthalpy resources being mainly connected with sedimentary formations.

In Europe, climate, market demand, reservoir conditions, and ecological reasons favour applications of geothermal energy mainly for: space heating; heating greenhouses; aquaculture; industrial uses; and bathing and balneotherapy. In a number of European countries, development is based on hydrothermal resources exploited from wells ca. 3 km deep (which can be named 'traditional' or 'classical'). Some of them started to dynamically develop shallow geothermal energy use in the past few years, based on heat pumps – an innovative and very prospective geothermal line. Both natural reservoirs (aquifers or rock formations), and man-made structures or reservoirs are treated as sources of geothermal heat. Some of these cases across Europe are presented in this lecture.

## 2. GEOTHERMAL CONDITIONS AND POTENTIAL

Generally speaking, the European continent is composed of three main geostructural units (Figure 2.1):

- Precambrian structures (including the Precambrian platform of Northwestern Europe occupying over half the total area of the continent);
- Palaeozoic folded structures of Central and Western Europe, partly covered by the Permian-Mesozoic sediments (maximum thickness amounts to 7-12 km within the territory of Poland);
- Alpine system of Southern Europe, running from the Iberian Peninsula to the Caucasus Mts.

Europe is characterized by low-to-moderate heat flow values. This parameter ranges from 30-40 $mW/m^2$ within the oldest part of the continent (the Precambrian platform) to 60-80 $mW/m^2$ within the Alpine system. Relatively high values of 80-100 $mW/m^2$ occur within seismically and tectonically active southern areas of Europe. Similar values are reported from some other regions, i.e. the Pannonian Basin and the Upper Rhein Graben (Hurter and Haenel [eds.], 2002).

Thermal regime and geological conditions result in the fact that Europe possesses mostly low-enthalpy resources. They are predominantly found in sedimentary formations. However, at attainable depths in several regions, high-enthalpy resources are also found, as in Iceland, Italy, Turkey, Greece, Russia and at some other islands and overseas territories (Guadeloupe, the Canary Islands). The main European geothermal fields under exploitation are in the Lardarello region (Italy); the Paris Basin (France); the Pannonian Basin (Hungary, Serbia, Slovakia, Slovenia, Romania); several sectors of the European Lowland (Germany, Poland); the Palaeogene troughs of the Carpathians (Poland, Slovakia); and other Alpine and older structures of Southern Europe (Bulgaria, Romania, Turkey).

Most recently, geothermal conditions and potential of Europe have been presented in the 'Atlas of geothermal resources in Europe' (Hurter and Haenel [eds.], 2002), a comprehensive work prepared thanks to the contribution of authors from over 30 states.

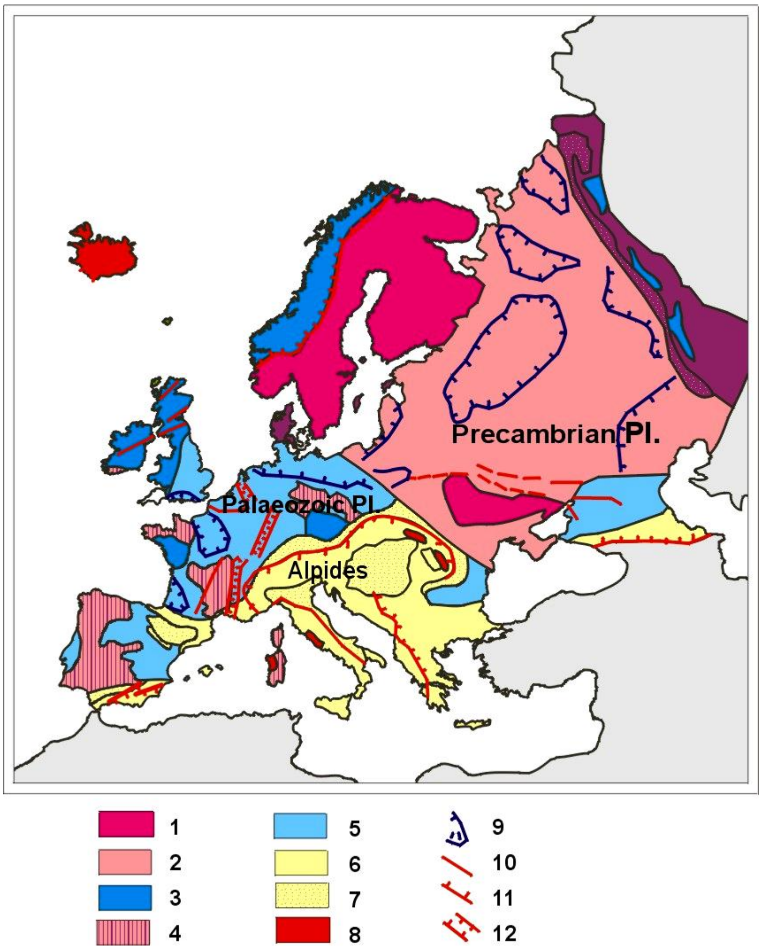


FIGURE 2.1: Geological setting of Europe (according to Stupnicka, 1989 - simplified)
*Precambrian platform:* 1. shields; 2. platform cover.
*Palaeozoic platform:* 3. Caledonides; 4. Variscides; 5. platform cover.
6. Alpides; 7. Alpine basins and grabens; 8. Cainozoic volcanic rocks;
9. Contours of troughs; 10. Faults; 11. Thrusts; 12. Rifts

## 3. GEOTHERMAL DIRECT USES – STATE-OF-THE-ART

Direct geothermal uses are reported from 28 European countries (Lund and Freeston, 2000). In 2000, total installed capacity was 5,714 MWt, while heat production amounted to 18,905 GWh/a, i.e. 35% of the world total (Lund and Freeston, 2001; Table 2.1).

It is worth noticing that, with the exception of China, industrial scale usage of geothermal energy is primarily found in Europe. As shown in Table 2.2, Iceland and Turkey have the greatest share in geothermal direct uses; followed by France, Hungary, Italy, Romania, Russia, Serbia, Slovakia, Sweden and Switzerland (over 2,000 TJ/y). It is worth noting that high geothermal heat generation in Sweden, Switzerland, Germany, and Austria was achieved by rapid heat pump development. The list of top world countries is dominated by the European ones: Iceland (4), Turkey (5), Russia (8), France (9), Hungary (10), Sweden (11), Italy (13), Romania (14) and Switzerland (15) (Lund and Freeston, 2000).

TABLE 2.1: Summary of geothermal energy use by continent in 2000, showing contribution of Europe (Fridleifsson, 2002; based on Huttrer, 2001 & Lund and Freeston, 2001)

| **Continent** | **Direct uses** | | | **Electricity generation** | | |
|---|---|---|---|---|---|---|
| | **Installed capacity ($MW_t$)** | **Total production** | | **Installed capacity ($MW_e$)** | **Total production** | |
| | | **(GWh/a)** | **(%)** | | **(GWh/a)** | **(%)** |
| Africa | 125 | 504 | 1 | 54 | 397 | 1 |
| America | 4355 | 7270 | 14 | 3390 | 23,342 | 47 |
| Asia | 4608 | 24,235 | 46 | 3095 | 17,510 | 35 |
| **Europe** | **5714** | **18,905** | **35** | **998** | **5745** | **12** |
| Oceania | 342 | 2065 | 4 | 437 | 2269 | 5 |
| TOTAL | 15,144 | 52,979 | 100 | 7974 | 49,263 | 100 |

TABLE 2.2: Europe – geothermal direct uses by countries in 2000 (compiled from Lund and Freeston, 2000)*

| **Country** | **Direct uses** | | **Electricity generation** | |
|---|---|---|---|---|
| | **Installed capacity ($MW_t$)** | **Total production (GWh/a)** | **Installed capacity ($MW_e$)** | **Total production (GWh/a)** |
| Austria | 255.3 | 447 | - | - |
| Belgium | 3.9 | 39 | - | - |
| Bulgaria | 107.2 | 455 | - | - |
| Croatia | 113.9 | 154 | - | - |
| Czech Republic | 12.5 | 36 | - | - |
| Denmark | 7.4 | 21 | - | - |
| Finland | 80.5 | 134 | - | - |
| France | 326.0 | 1,360 | 4.2 | 24.6 |
| Germany | 397.0 | 436 | - | - |
| Greece | 57.1 | 107 | - | - |
| Hungary | 328.3 | 785 | - | - |
| Iceland | 1,469 | 5,603 | 170 | 1138 |
| Italy | 325.8 | 1,048 | 785 | 4403 |
| Lithuania | 21.0 | 166 | - | - |
| Macedonia | 81.2 | 142 | - | - |
| Netherlands | 10.8 | 16 | - | - |
| Norway | 6.0 | 9 | - | - |
| Poland | 68.5 | 76 | - | - |
| Portugal | 5.5 | 10 | 16 | 94 |
| Romania | 152.4 | 797 | - | - |
| Russia | 307.0 | 1,703 | 23 | 85 |
| Serbia | 80.0 | 660 | - | - |
| Slovakia | 132.3 | 588 | - | - |
| Slovenia | 42.0 | 196 | - | - |
| Sweden | 377.0 | 1,147 | - | - |
| Switzerland | 547.3 | 663 | - | - |
| Turkey | 820.0 | 4,377 | 20.4 | 119.73 |
| United Kingdom | 2.9 | 6 | - | - |
| **Europe total** | **5714** | **18,905** | **998** | **5745** |
| World – total | 15,144 | 52,979 | 7974 | 49,263 |

* In the cases of Poland, Turkey, and some other countries, the figures presented have increased since 2000 as new installations were put into operation

Geothermal power generation using high-enthalpy steam takes place in only a few European states only, i.e. Iceland, Italy, Russia, Turkey, and in overseas territories of France (Guadeloupe), and Portugal (Azores). In 2000, geothermal electricity generation in Europe contributed only 10% of total world production (Table 2.1). Recently, the list of European geothermal power producers has been extended by Austria; in this country, two binary power plants based on low-enthalpy resources have been on-line since 2001 (Pernecker, 2002; Legmann, 2003). In some other countries advanced works aimed at launching binary stations are in progress (i.e. Germany, Hungary, Slovenia; Jung et al., 2003; Krajl, 2003).

## 4. GEOTHERMAL IN ENERGY POLICIES AND STRATEGIES

In the countries of continental Europe, energy plans and strategies treat geothermal as one of the local sources and a component of the renewable energy mix, along with wind, solar, hydro and biomass. Today, the share of all renewables in CEE countries amounts to max. 4–5%. In the case of the European Union countries, the assumed share of renewables in energy production is predicted to reach 12% in 2010, and 20% in 2020. Although there are promotional programmes, economical and legal incentives, as well as local and international projects, geothermal energy production is often underrated as compared to other renewables. As far as geothermal and renewables are concerned, CEE countries often have worse development conditions. Having frequently better natural geothermal conditions than in EU-countries, they encounter difficulties related with the on-going economic and social transformation. The share of all renewables in the total primary energy production in all CEE countries is planned to reach a level from ca. 2% (Bulgaria) to ca. 7.5% (Poland) in the years 2005 to 2010, and 12 to 15% by 2020. However, fossil fuels (plus nuclear in some cases) will still play the main role.

## 5. METHODS AND TRENDS OF GEOTHERMAL EXPLOITATION AND USE

Geothermal resources in Europe are exploited and implemented in several ways. They mainly depend on:

- Depth of geothermal reservoir;
- Lithology of reservoir formation;
- Main reservoir and exploitation features and parameters.

It is crucial to preserve the renewability or sustainability of a geothermal reservoir. Besides, legal and environmental regulations established in the specific countries are of concern. Generally, there are three production and maintenance options for geothermal reservoirs and systems: (1) Exploitation of deep reservoirs; (2) Exploitation of shallow resources; (3) Hot Dry Rock technology (R&D stage).

Some selected issues related with the production of deep and shallow geothermal resources in various European countries follow further in the text.

### 5.1 Exploitation of deep reservoirs.

Water temperatures at outflows are from about 30 to a maximum of 90-110ºC; TDS varies from 1 to 300 g/l. Waters are produced through a spontaneous artesian outflow or are pumped. Aquifers are connected mostly with sedimentary formations, such as limestones, dolomites, or sandstones. Some systems are connected with crystalline or metamorphic rocks. In the majority of cases, exploitation is carried out in:

- Closed well systems, i.e. doublets of production and injection wells. Geothermal heat is extracted through heat exchangers;
- Open well systems, when only production wells ('singlets') are working. In some cases, when the injection is not necessary, the cooled geothermal water after passing through heat exchangers (or at least a part of it) is disposed into surface water reservoirs (i.e. river, ponds) or it is used for other practical purposes, for instance as drinking water or for swimming pools.

Water production from sedimentary rocks is related with some specific phenomena and problems. They have an influence on obtaining satisfactory reservoir and production parameters, and maintenance of long-term water production. Some of them are typical of all geothermal systems, some mainly depend on the lithological type of reservoir rocks. These are, e.g. change of production and injective properties; colmatation and plugging of the near-hole zone; scaling; corrosion; etc. Suitable methods for a successive treatment and maintenance of such reservoirs and wells have been worked out and implemented in a number of countries, e.g. France with its carbonate reservoirs and Germany with sandstones. Depending on the temperature of geothermal water at the outlet, the installments work on geothermal only, but sometimes they are used along with traditional fuels (integrated systems).

### 5.2 Exploitation of shallow resources.

In this case, the heat of water, soil or rock formation is extracted through borehole heat exchangers/heat pump systems or heat pumps (different layouts and schemes). These installations are frequently parts of integrated heating systems. Significant developments of this method were started at the beginning of the 1990s in several European countries (Switzerland, Germany, Austria, Sweden), similar to the USA, Canada or Japan. It opened a new line in geothermal uses, creating prospects for other European countries, e.g. because of the lack of limitations in the installation and economical profitability (provided, the prices for these systems will drop). Roughly speaking, two types of recovery can be distinguished here:

- Natural (i.e. created by nature);
- Man-made – structures or reservoirs formed as a by-product of man's activity, oriented to other purposes than geothermal. Here we have old workings filled with warm water or air, rooms at the diapirs formed in the course of underground production (salt leaching) – type of underground workings, as well as tunnels drilled in rock masses which open up warm waters from the dewatering processes.

### 5.3 Hot dry rock.

Large international R&D projects on hot dry rocks, HDR, are being developed in France and Germany. New ones are expected to start soon (e.g. Jung et al., 2003; Krajl, 2003).

## 6. DEEP HYDROTHERMAL RESOURCES IN SEDIMENTARY FORMATIONS – SOME ASPECTS

### 6.1 Carbonate reservoirs - France

France is number three among leading European countries in geothermal direct uses (Laplaige et al., 2000; Table 2.2). The geothermal district heating systems operating in the Paris region are well known. The first geothermal district heating system was opened in 1969 there. The development is related to hydrothermal resources exploited in a "classical" way, i.e. through the doublets of relatively deep (1.5-2.5 km) wells. As a routine, the injection of cooled geothermal fluid back into reservoirs has been practised.

Geothermal resources are mostly low-enthalpy, connected with sedimentary basins. The main ones are the Paris Basin and the Aquitane Basin. The reservoirs are predominantly connected with limestones of Mesozoic (Jurassic) age in the Paris Basin, and dolomites and sandstones in the Aquitane Basin.

The Paris Basin (Figure 2.2) is a large regional structure filled with Mesozoic and Cainozoic series. They contain numerous aquifers, including geothermal. The geothermal gradient is about 4ºC/100 m. Most of geothermal space heating systems produce warm water discharged by the Dogger (Middle Jurassic) limestones (Ungemach, 2001). Temperatures of the produced water vary between 60 and 80ºC, while the TDS varies from 5 to 35 g/dm$^3$ (Tarkowski and Uliasz-Misiak, 2002). The waters have a relatively high TDS, and amount of gases, while the prevailing water type is Cl-Na. Owing to the chemical composition and presence of hydrogen sulfide, these waters are corrosive and must be injected back.

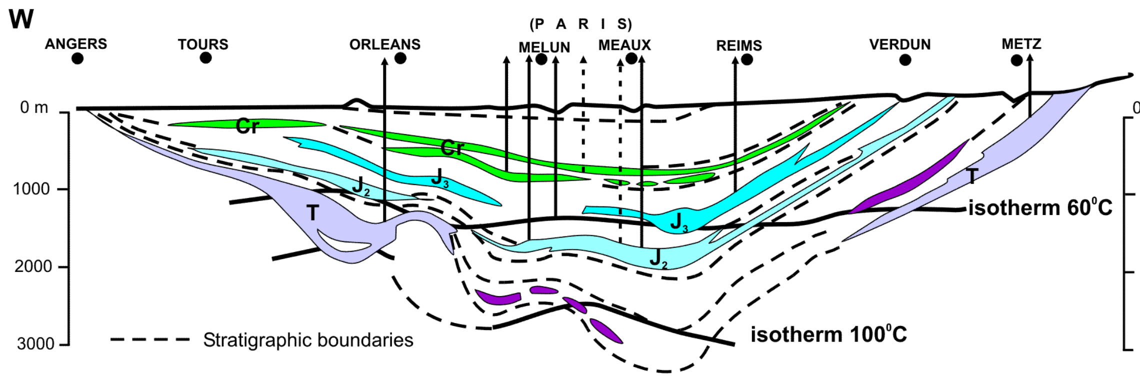


FIGURE 2.2: A sketch cross-section through the Paris Basin
(Tarkowski and Uliasz-Misiak, 2002)
T – Triassic, $J_2$ – Middle Jurassic (Dogger), $J_3$ – Upper Jurassic (Malmian), Cr – Cretaceous

The peak period of geothermal space heating in France was in 1980-1986. During those years, 74 plants were in operation: 54 in the Paris Basin, 15 in the Aquitaine and 5 in other regions (Laplaige et al., 2000). The crisis in development occurred 1986-1990. It was caused mostly by the drop in energy prices, and technical difficulties affecting geothermal installations in the Paris Basin. The latter were expressed by the scaling on the metal parts of geothermal loops due to the corrosiveness of the sulphide-rich geothermal water. Several initiatives and actions were undertaken to improve the economical situation of the plants, and to resolve the technical problems in the successive several years.

To solve technical problems – scaling, corrosion (and also blocking and damaging the reservoir by products of corrosion and scaling introduced to the reservoir with the injected water) – the technical projects embraced two priorities: (1) curative techniques for the elimination of scale and the reconditioning of the boreholes to restore the hydraulic well characteristics and; (2) the preventive methods for mitigating or avoiding corrosion and scaling processes. Special equipment was introduced to the wells (WBTT – well bottom treatment tubing) for performing the soft acidizing and continuous injection of inhibitors. The results were very positive. It is enough to say that a ten-fold decrease in casing corrosion was noted after the installation of such a treatment. After technical problems had been solved, several years were oriented for optimising geothermal heating networks and connecting new receivers (Laplaige et. al., 2000).

Nowadays, out of 74 plants operating in 1986, 61 are still on-line, the bulk of them (34) in the Paris Basin. All geothermal plants in the Paris Basin are based on the well doublets drilled in the period

1981-1987. They supply space heating and domestic warm water (Laplaige et al., 2000; Ungemach, 2001). Both vertical and deviated wells are in use. They encounter geothermal aquifers at the depths between 1430 and 2310 m. Maximum water flowrates are 90-350 $m^3/h$. In most cases, submersible pumps are installed. However, some of the wells are artesian. Wellhead water temperatures vary from 66 to 83ºC. In some cases, the geothermal plants work combined with gas boilers. After passing heat exchangers, cooled geothermal water (40-60º C) is injected back (Table 2.3).

TABLE 2.3: Geothermal doublets operating in the Paris Basin, 2000 (compiled from Ungemach, 2001)

| **Drilled years** | **Number of doublets** | | **Total depths of wells** | | **Water flowrate ($m^3/h$)** | **Wellhead temperat. (ºC)** | **Method of product.** | **Remarks** |
|---|---|---|---|---|---|---|---|---|
| | **Working** | **Abandoned** | **Vertical (m)** | **Deviated (m)** | | | | |
| 1981-1987 | 34 | 20 | 1430-1790 | 1710-2310 | 90-350 | 66-83 | Submersible pumps, Artesian | Gascogeneration in some cases |

As mentioned before, the stability of the operation of geothermal systems in France was achieved thanks to elaboration and introduction of appropriate rehabilitation and preventive methods - tailored to carbonate and sandy reservoirs. They were aimed at mitigating or avoiding well damages, corrosion and scaling thus to maintain production and injectivity indices. One of the methods elaborated and successfully implemented is soft acidizing (Ungemach 1997). It can also be applied in other sedimentary systems.

## 6.2 The Paris Basin vs. other Mesozoic sedimentary geothermal systems in Europe

Mesozoic sedimentary basins cover the area of many European countries. They are related with production of perspective geothermal systems in France, Germany, Poland, and Denmark. Table 2.4 gives the main characteristics of the Paris Basin (Middle Jurassic- Dogger) and Jurassic formations of the Polish Lowland which contain numerous geothermal aquifers too.

TABLE 2.4: Jurassic formations of Paris Basin and Polish Lowland – comparison of main geothermal parameters (Tarkowski and Uliasz - Misiak, 2002)

| | **Paris Basin (Dogger-Middle Jurassic)** | **Polish Lowland – Jurassic basins** | | |
|---|---|---|---|---|
| | | **Malmian (Upper Jurassic)** | **Dogger (Middle Jurassic)** | **Liassic (Lower Jurassic)** |
| Area of occurrence ($10^3$ $km^2$) | ~110 | 75 | 93.5 | 88.5 |
| Depth to top of aquifer (m b.s.l.) | 0-1800 | 1000-3200 | 1000-3500 | 500-3800 |
| Total thickness (m) | 100-150 | 100 | 80-100 | 200-250 |
| Reservoir rocks | limestones | limestones | sandstones | sandstones |
| Permeability (D) | 0.5-20 | 0.1-2.14 | 0-0.42 | 0.1->1.50 |
| Water flowrate ($m^3/h$) | up to 320 | 0.3-60.5 | 1-29 | 1->100 |
| Reservoir temperatures (ºC) | 25-85 | 25-96 | 25-105 | 25-114 |
| TDS ($g/dm^3$) | 6.5-35 | 0.3-129 | 0.4-107 | 0.3-127 |
| Number of geothermal installations | 34 | - | - | 2 |
| Type of use | Space heating and warm water | - | - | Space heating and warm water |

It results from Table 2.4 that the Dogger formation of the Paris Basin represents very similar parameters as the Upper Jurassic (Malmian) formations in Poland as far as lithology and reservoir rocks' thicknesses are concerned. In the former ones, waters appear at smaller depths but reach higher temperatures and higher flowrates than in Poland (which is connected, among others, with conducting the inflow stimulation treatments in France). Despite a considerable TDS value, over 30 geothermal space-heating plants are operational in the Paris Basin. The case of this Basin provides evidence that such basins are perspective for geothermal space-heating and other direct uses. There are many other such places across Europe (still waiting to be exploited) offering similar possibilities, e.g. Poland.

### 6.3 Sandstone reservoirs – Germany

In Germany, geothermal direct use development is based both on shallow and deep resources. This country is one of the top European leaders in geothermal production (Table 2.2), having great dynamics of development, especially in the first domain (heat pumps technology). Some geothermal space-heating plants are exploiting water from deep sedimentary formations, as is the case of Neustadt–Glewe in NE Germany. The plant has been in operation since 1995. The total installed capacity is 16.4 $MW_t$, out of which 6 $MW_t$ comes from geothermal water **(**Menzel et al., 2000).

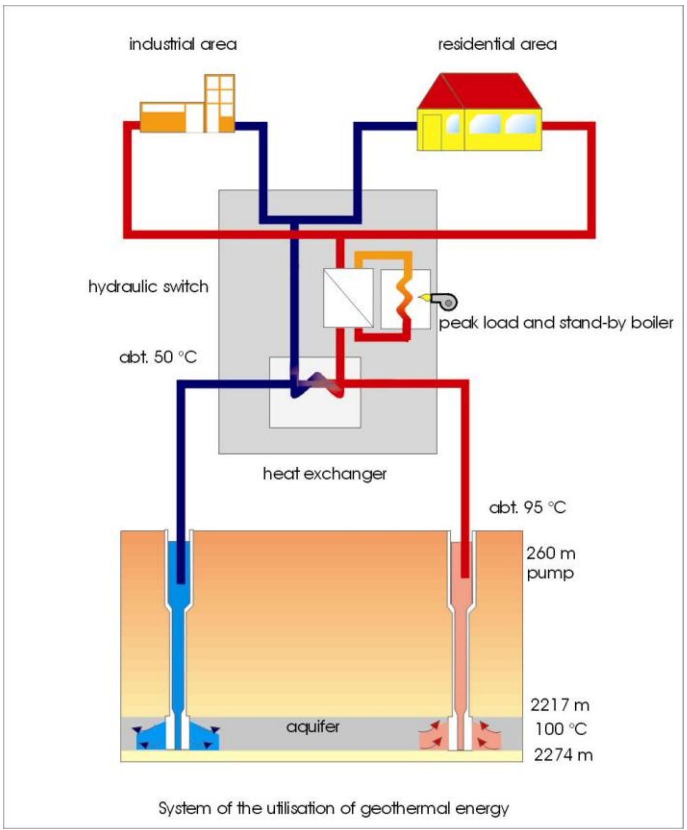


FIGURE 2.3: A scheme of the Neustadt-Glewe geothermal space-heating plant, Germany (Menzel et al., 2000)

The reservoir rocks are the Triassic sandstones situated at the depth of 2217-2274 m. They are exploited through the doublet of production and injection wells. Heat is extracted by heat exchangers (Figure 2.3). Production amounts to about 180 $m^3$/h of 95-97ºC water, while the TDS are high and reach 220 g/$dm^3$ (Table 2.5). The main ions are sodium and chloride, then calcium, magnesium, potassium, sulphate and some rare elements. The water contains about 10% of gas including carbon dioxide, nitrogen, and methane. The cooled geothermal water is injected back to maintain the pressure and also because of its high TDS.

To avoid corrosion and precipitation problems, specific materials were applied: glass-fiber tubes, resin-lined steel tube parts and measures such as inertisation by means of nitrogen loading. The materials and equipment stand up to the extreme temperatures, aggressive brine and pressure conditions.

However, the injection pressure has been increasing in the course of exploitation. This problem was caused by the sedimentation of solid particles on the filter section of the injection well. The solids consisted mostly of acid-soluble iron hydroxides and aragonite. The removal of these components was done by using the soft acidizing method – i.e. by adding highly-diluted HCl lowering the pH value of the injected cooled geothermal water. For two days, ca. 4 $m^3$ of 15% HCl were systematically added to the injected geothermal water, which had a total volume of ca. 1600 $m^3$ (Menzel et al., 2000). As a result, the injectivity index of the injection well was considerably increased (Figure 2.4).

TABLE 2.5: Main data on the sandstone geothermal reservoir in Neustadt –Glewe, Germany (Menzel et al., 2000)

| | |
|---|---|
| Depth of the aquifer | 2217-2274 m |
| Lithology | Sandstones |
| Stratigraphy | Triassic (Keuper/Rhetian) |
| Temperature gradient | 4.06ºC/100m |
| Effective porosity | 22% |
| Permeability | 0.5-0.8 x $10^{12}$ $m^2$ |
| Reservoir temperature | 98ºC (2223 m) |
| Number of wells | 2 (1 production and 1 injection) |
| Distance between wells | 1,350 m |
| Productivity | 183 $m^3$(h·MPa) |
| Injectivity | 265 $m^3$(h·MPa) |
| Wellhead temperature | 95 - 97ºC |
| TDS | 220 g/$dm^3$ |

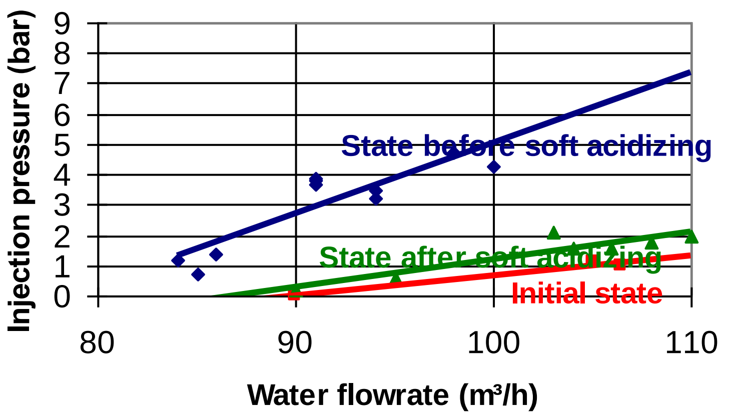


FIGURE 2.4: The Neustadt-Glewe geothermal space-heating plant, Germany – soft acidizing results shown by significant lowering of the injection pressure (Menzel et al., 2000)

The soft acidizing method gives good results in sedimentary geothermal environs, both for rehabilitation of well casings, and the reservoir rock formation itself. What is most important, however, is that it can be applied during the geothermal doublet exploitation (no breaks in their operation), and does not require using heavy equipment and rigs. The soft acidizing is carried out with the use of light equipment and coiled tubing. This economically profitable method gives more permanent results than other well and reservoir rehabilitation and maintenance methods.

The method of soft acidizing and related problems and technologies applied to carbonate and sandstone geothermal reservoirs and adequate study cases are described in details in specialist papers (e.g. Seibt and Kellner, 2003; Ungemach, 1997; Ungemacht, 2001, Ungemach 2003).

## 6.4 Main options of cooled geothermal water disposal

In a majority of space-heating systems, geothermal water after heat extraction is injected back to the reservoir. However, in some particular situations, spent water after passing through heat exchangers or heat pumps is not re-injected, but applied for some practical needs. In the operational European cascaded or multipurpose plants, the water is applied in pools or for balneotherapy purposes. In a smaller number of cases, such water may meet some standards and is used as tap water (i.e. TDS less than 1 g/$dm^3$ and appropriate chemical composition). Some examples are listed in Table 2.6.

TABLE 2.6: Methods of disposal of cooled geothermal water from heating-oriented systems in Europe – some examples (compiled from Bujakowski, 2001; Dlugosz, 2003; Laplaige et al., 2000; Menzel et al., 2000; Ungemach, 2001 and other data)

| Type of reservoir rocks | Example | Method of exploitation | TDS, ($g/dm^3$) | Wellhead temperature (ºC) | Method of disposal of cooled geothermal water |
|---|---|---|---|---|---|
| Carbonates | Paris Basin France | Doublets | 6.5-35 | 66-83 | Injection |
| | Podhale region Poland | Doublet | 2.5-2.7 | 82-87 | Injection |
| Sandstones | Neustadt – Glewe, Germany | Doublet | 220 | 95-07 | Injection |
| | Mszczonow, Poland | Singlet | 0.5 | 41 | No injection, cooled water for drinking |
| | Slomniki, Poland | Singlet | 0.4 | 17 | No injection, cooled water for drinking |

Presently, and in the coming years, closed geothermal exploitation systems will prevail. This is caused by the necessity to preserve the renewable features of reservoirs, mitigate corrosion and scaling, and meet the environmental requirements.

## 7. SHALLOW GEOTHERMAL RESOURCES – SOME ASPECTS

### 7.1 Geothermal heat pumps – Switzerland

#### 7.1.1 General

Switzerland belongs to the world's leaders in shallow geothermal resource applications through heat pumps. It is among the world's top countries along with the USA, Sweden, Germany and Austria (Lund, 2001b). It is worth noting that in the 1970s, this country did not carry out geothermal uses (except for bathing and swimming in some spa resorts). Bearing in mind the geothermal capacity of about 70 $W_t$ per capita, this country occupies world rank three in direct uses after Iceland (5344 $W_t$) and New Zealand (75.4 $W_t$). Statistically, it was estimated that one shallow heat pump was installed within every two $km^2$ of country area (Rybach et al., 2000). Significant and rapid development of geothermal direct uses has been made in the last decade. Numerous promotions, economical incentives, research, and technology make Switzerland an example to follow.

Generally, geological structure and conditions of the country do not favour the occurrence of deep geothermal aquifers and systems. However, geothermal research developed owing to the risk guarantee system for aquifer drilling more than 400 m deep. This system was available in the years 1987-1998 and brought about some positive results. Heat pumps are developed to a great extent. The long–term governmental policy greatly favours it.

According to the data from 2000 (Rybach et al., 2000), the total installed geothermal capacity was about 550 $MW_t$ while the annual energy use was about 2400 TJ (Table 2.7). The essential contribution to these figures was by geothermal heat pumps; 500 $MW_t$ (91%) and 1980 TJ (82.5%), respectively (Rybach et al., 2000). Figure 2.5 illustrates the contribution of different geothermal sources to the total heat production in Switzerland in 1999.

TABLE 2.7: Switzerland – summary of geothermal direct uses, 2000 (Rybach at al., 2000)

| Type of use | Installed capacity ($MW_t$) | Annual energy use (TJ/a) |
|---|---|---|
| Space-heating<br>Air conditioning<br>Snow melting<br>Bathing and swimming | 20<br>2.2<br>0.1<br>~25 | 132<br>4.0<br>0.3<br>~270 |
| SUBTOTAL | ~50 | ~400 |
| Heat pumps | 500 | 1980 |
| **TOTAL** | **~550** | **~2400** |

### 7.1.2 Main types of shallow geothermal energy extraction

In Switzerland, some spa resorts use natural geothermal spring waters for balneotherapy, and, to some extent, for space heating of spa facilities. What concerns successful implementation of geothermal energy produced from deep aquifers, one geothermal doublet has been in operation near Basel (N-Switzerland). It works in an integrated scheme, supplying district heating systems in two nearby localities on the Swiss and German sides of a boundary (Rybach et al., 2000).

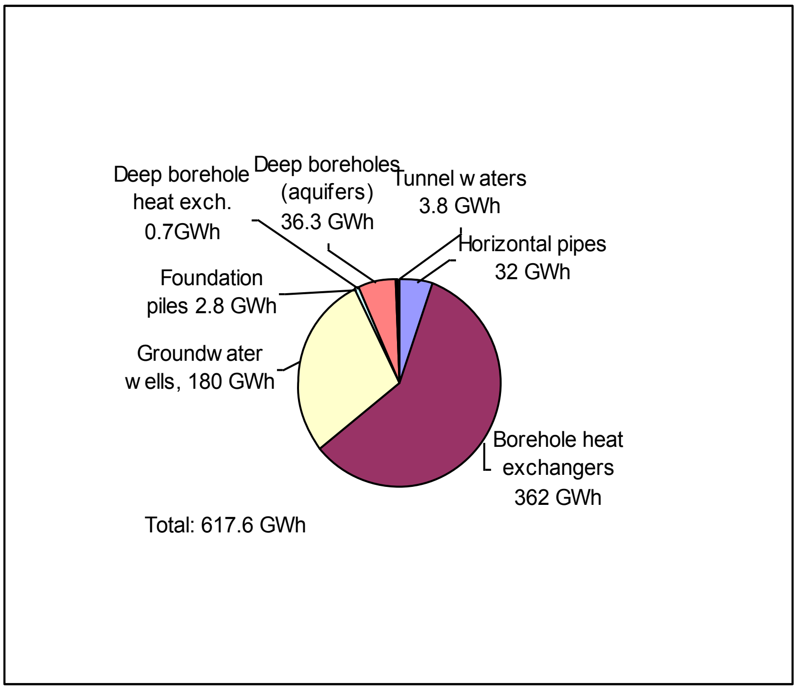


FIGURE 2.5: Contribution of different geothermal sources to the total heat production in Switzerland in 1999 (Rybach et al., 2000)

The entire story on rapid geothermal use development - a real 'boom' in fact - in that the country is connected with shallow geothermal resources involving heat pumps and borehole heat exchangers. Four main types of technology to tap them are as follows (Rybach, 2001):

- Groundwater wells;
- Horizontal coils;
- Borehole heat exchangers;
- Geostructures (foundation piles, concrete walls).

It should be added that some contribution to the total amount of heat extracted through heat pumps comes from alpine tunnel water. Table 2.8 depicts shallow geothermal heat production in Switzerland using the main types of technology listed above.

TABLE 2.8: Geothermal (ground-source) heat pumps in Switzerland, 2000
(according to Rybach et al., 2000)

| Number of units | Ground / water temperature (ºC) | Typical heat pump rating or capacity (kW) | Type* | COP | Equivalent full load (hrs/y) | Thermal energy used (TJ/a) |
|---|---|---|---|---|---|---|
| ~17,000 | 10 | 19 | V/H | 3 | 1600 | 1240 |
| ~ 4,000 | 10 | 40 | W (groundwater) | 3 | 1600 | 614 |
| 7 | 23-69 | 2500 | W deep aquifer | 3 | 1600 | 114 |
| 6 | 15 | 500 | W (tunnel water) | 3 | 1600 | 11 |
| Total ~ 21,000 | | | | | | 1979 |

* Type of installation: V – vertical ground coupled; H – horizontal ground coupled; W – water source

In 2000, over 20,000 heat pump systems were installed, with a total of about 4000 km of borehole heat exchangers (Rybach et al., 2000). For sure, these figures have increased to the present year (2003). For 1995-2000, it was estimated that the number of installations increased by more than 15% annually. Every third newly built, single-family house in Switzerland has its own heat pump system. Installations are based on various types of these installments (e.g. air sources, geothermal) including about 40% of heat pumps which have a geothermal source. What is interesting: although the installation of air-source heat pumps is much cheaper as compared with geothermal, generally lower seasonal performance coefficient of the air source heat pump is the main reason for the high percentage of geothermal heat pumps. Both technical and economic factors contributed to the observed heat pump boom. Among available schemes and systems, the most popular borehole heat exchanger/heat pump heating system involves one or more 50-200 m deep boreholes.

### 7.1.3 Tunnel water as a source for heat pumps

Another prospective field of geothermal heat pump usage - specific for Switzerland as an Alpine country – represents the implementation of thermal energy contained with drainage waters met during tunnelling new roads and railways through mountain massifs, or drained constantly out of already existing tunnels. The temperatures of such waters are in range from 10-25ºC. About 1,200 tunnels with a total length of 1,600 km have been built in the country. Several new one are being constructed, the longest of which will be over 50 km (Wilhelm and Rybach, 2003).

In several cases, the temperature and flowrate of tunnel water led to the use of their potential for small space-heating and domestic warm water preparation systems of residential buildings in sites located close to the tunnel portals. Because of economic reasons, the distance between portal and consumer should be shorter than 1–2 km.

A significant number of existing alpine tunnels represents a total thermal potential of 30 $MW_t$, enough to provide several thousands of people with thermal energy. Moreover, about 40 $MW_t$ are estimated to be available from drainage water at the portals of two new tunnels under construction (2003): with lengths of 35 km and 57 km. This theoretical potential is being a subject of detailed modelling and evaluation, to give more realistic values which could be used for planning of the so-called portal-near heating systems (Wilhelm and Rybach, 2003).

### 7.2 Geothermal energy from underground mines – Poland[1]

#### 7.2.1 General (by Z. Malolepszy)

In recent decades, coal mining has declined in many regions of the world, causing abandonment of underground mines. Problems of reclamation and utilization of surface and underground remains of the former mines arise as an important aspect of sustainable development of post-mining industrial areas. There are many abandoned coal fields around Europe and the world, e.g. in France, Germany, Great Britain, the Netherlands, Poland, Spain, Slovakia and Ukraine. Some of them are the subjects of reservoir engineering studies and development of geothermal utilization in abandoned workings. Several installations, based on geothermal heat pumps, are already working in Canada, Germany, and Scotland. These show that mines that have extracted fossil fuels in the past can produce clean and renewable geothermal energy. Several examples show that temperatures of water in flooded mines reach more than 45-50°C at depths of up to 1000 m.

Abandoned, water-filled mine workings contain tens of millions of cubic meters of warm waters. They constitute a significant, but little-studied, geothermal resource that can be used with the application of heat pumps for space-heating, recreation, agriculture, and industry. Direct use of warm water from the mines is possible in, for example, snow-melting systems.

Water reservoirs can be found in almost all kinds of underground mines after termination of exploitation and abandonment of mine workings. In coal mines, extraction of laterally distributed coal seams forms large areas of horizontal or sub-horizontal zones of empty openings and voids which are defined, after flooding of the abandoned mine, as water reservoirs. The site-specific conditions of each coal field or coal-mining area impact on the potential utilization of reservoirs for geothermal purposes (Figure 2.6).

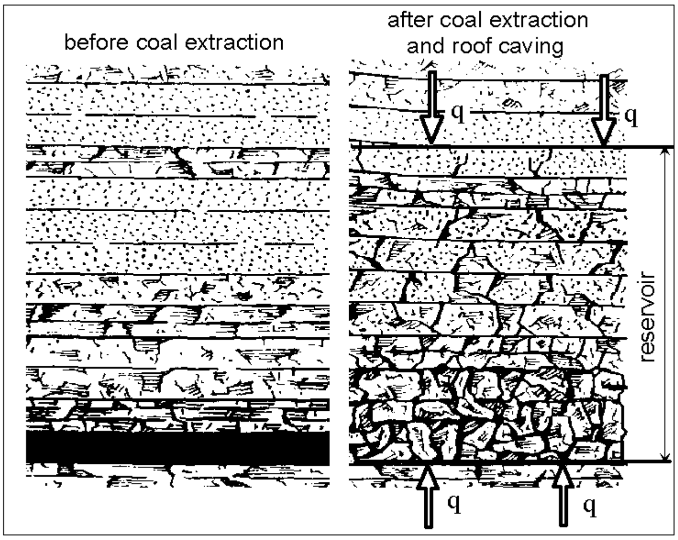


FIGURE 2.6: Sketch of water reservoir in the mine workings after extraction of coal seam (black layer) and caving in of the roof; arrows q mark heat inflow (Malolepszy, 2003)

Rock formations of coal fields generally consist of a variety of thin intercalated layers of terrigenous deposits which are horizontally bedded in most cases. Claystone, siltstone, and sandstone rather than conglomerates are characterized by low porosities and permeabilities.

The hydrogeological regime of an abandoned mine gradually returns to its natural state if de-watering systems are terminated. At present, that process is only possible in isolated mining areas without hydraulic connection to adjacent mines that are still in operation. Therefore, de-watering systems in abandoned mines are maintained, and waters are pumped from levels at which connected mines are preserved from. The deepest levels of abandoned workings are flooded out with colder water flowing from the shallower levels.

#### 7.2.2 Coal mines as potential geothermal reservoirs (by Z. Malolepszy)

In Poland, along with the development of geothermal space-heating based on deep wells and, say, traditional schemes, shallow geothermal represents another option. It concerns not only naturallyoriginated reservoirs, but also 'man-made' geothermal reservoirs in underground mines. The latter concerns recovery of geothermal heat from underground mines (coal, or ores mines), contained in ventilation air and warm waters pumped out from the mines.

For several years, R&D work has been conducted on this specific but interesting subject, especially as far as the Upper Silesian Coal Basin is concerned. This is one of the biggest hard-coal basins in Europe, a basis for the development of a strong electro-energy branch in Poland. Since the 1990s, this branch has been in progress of restructuring. One of the results will be the closing of many mines (some of them have already been closed). Basic theoretical studies and evaluation of geothermal potential of coal mines have been made by Malolepszy (Malolepszy, 1998; Malolepszy, 2003), using, among other, numerical modelling methods and the TOUGH2 simulator.

Generally, coal fields are located in areas of mean geothermal gradient varying between 17 and 45°C/km, with an average value of 32°C/km in Polish coal fields. These values give temperatures of 30-50°C at the deepest levels of the mines (1000-1200 m). Terrestrial heat flow measured in coal-mining areas does not exceed average values, which for European coal fields, fit in the range of 40-80 mW/m$^2$ with regional anomalies of up to 110 mW/m$^2$ in south-western Upper Silesian Coal Basin where formation temperatures are higher. Horizontally bedded rock layers with low heat conductivity coefficients form caprocks for the inflow of geothermal heat. It is expected that thermal anomalies occur beneath thick layers of coal-bearing formations, as in many other sedimentary basins. The local anomalies are observed at exploitation depths of 1000 m in coal-mining areas where there are vertical tectonic structures and vertical or inclined rock stratification, but they do not have much impact on overall formation temperatures.

Spontaneous coal-seam fires in mines often occur in protecting pillars and other unexploited parts of the mines. Together with sulfphide mineral oxidation processes, they cause considerable local temperature anomalies which disturb the natural thermal regime of the mine. Flooding of the abandoned mines extinguishes fires, but the oxidation processes can be continued by oxygen dissolved in the water.

The water reservoir in a mine working is created by extraction of coal and waste rock. The volume of the mined spaces is equal to the volume of removed material, but after removal of the pillars supporting the roof, the volume of the remaining openings decreases significantly due to subsidence and back-filling. Depending on natural and technological conditions, 5-40% of the initial volume remains open and after flooding of the mine, is filled with water. In many cases, the convergence of the roof with the floor occurs under high pressures at deep levels. Generally, debris and rubble which have fallen from the roof protect against this. A considerable part of the volume of a reservoir is distributed above the extracted coal seam in the form of fractures created in the de-stressed roof.

Many of the shafts, drifts, and roadways remain open if the roof-supporting devices have not been removed. These open tunnels, accounting for considerable volumes in the mine as a whole, could act as possible routes of inflow/outflow into/from reservoirs in mine workings.

### 7.2.3 Proposal of practical implementation

Despite the great interest, the practical use of heat from the underground mines in Poland has not entered the application stage yet. Among the main causes are problems with restructuring the coal industry branch in Poland. This option is still awaiting some attention, which hopefully will be the case some day.

A technological project and economical analysis was done concerning the use of warm water pumped out from one selected coal mine for stenothermal fish farming (African catfish). The parameters of water pumped out of the mine are: flowrate ca. 180 m$^3$/h and temperature about 20ºC. The fish farm would be sited near the shaft, with which water is pumped out to the surface. The existing surface infrastructure can be also used for farming purposes. The heat would be recovered through heat pumps. The yearly production could reach over 110 tons of fish. The results of the analyses indicate that the installation could be constructed within less than 10 months. It would be profitable, and the simple payback period was estimated for 5 years. At the same time, it would be a solution to the unemployment problem for miners dismissed from the closing mines (Bujakowski, 2001).

### 7.3 Salt dome structures as potential geothermal energy sources - Poland

Salt diapirs – specific tectonic structures formed of Permian (Palaeozoic) saline formations are a subject of the newest geothermally-oriented research in Poland (Bujakowski [ed.] et al., 2003). Such structures are also known from other European countries, e.g. Germany.

Generally speaking, salt domes were formed by the pushing of plastic saline formations upward to the surface owing to the pressure of a few kilometre thick layer of younger sedimentary rocks (from Triassic to Quaternary). Such diapirs have their roots at 5 to 8 km b.s.l., whereas their roof parts are often some hundred to some tens of metres from the surface only (Figure 2.7). Sporadically, their top parts, the so-called gypsum caps, may manifest as outcrops. An example of a salt-dome and its inner structure is shown in Figure 2.8.

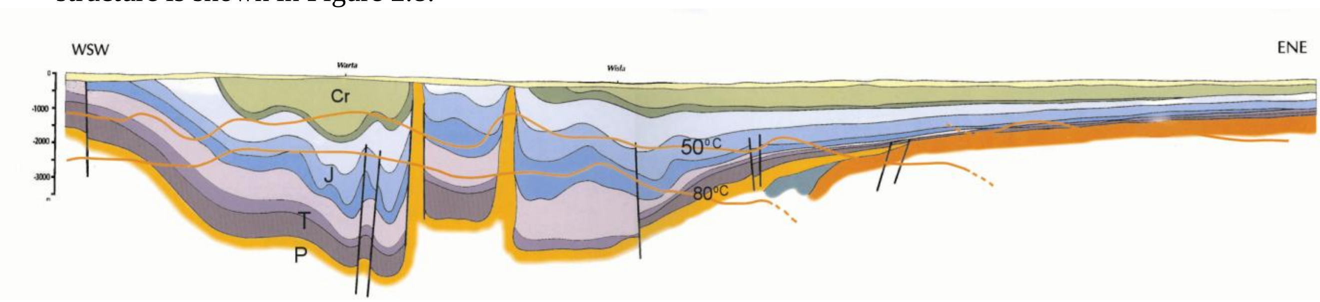


FIGURE 2.7: Geological cross-section through Poland; note Permian (P) salt diapers piercing younger formations (in: Gorecki [ed.], 1995)
P- Permian, T – Triassic, J – Jurassic, Cr – Cretaceous

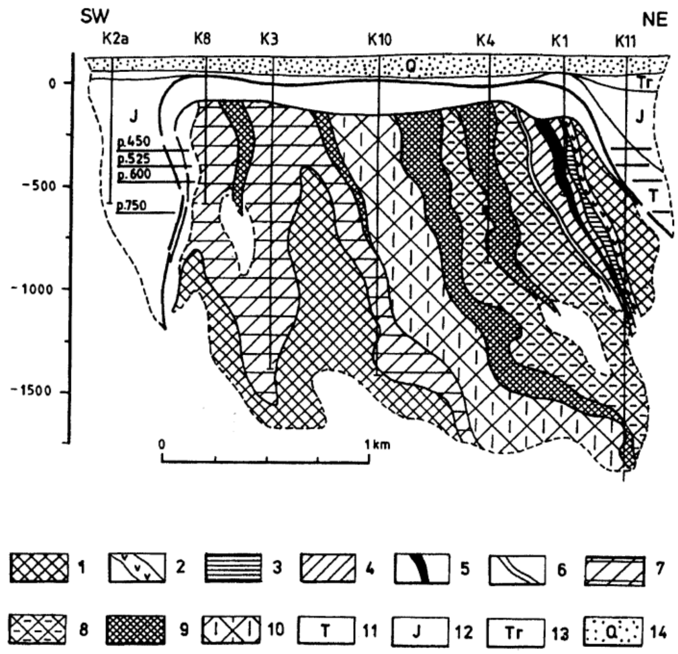


FIGURE 2.8: An example of salt-dome structure, Klodawa, Polish Lowland Province (Szybist, 1995)
1. Older Halite; 2. Older Potassium Salt; 3. Grey Salt Clay and Main Anhydrite; 4. Younger Halite; 5. Younger Potassium Salt (kizeritic karnalite); 6. Karnalite-bearing association; 7. Younger Salts Association; 8. Brown Zuber and Clayey Salts; 9.Youngest Halite (pink); 10. Red Zuber with Clayey Salts; 11. Triassic; 12. Jurassic; 13. Tertiary; 14. Quaternary

As compared to other rocks, salt has exceptionally good thermal properties, high thermal conductivity from 6 to 7 W/mK, exceeding 2-3 times the values for the neighbouring rocks (limestones, sandstones, siltstones). Heat is cumulated in the saline structures, causing a growth in temperature in the neighbouring rocks. Diapirs are migration paths ('thermal bridges') facilitating the Earth's heat transport from greatest depths to the surface. Increased temperatures can be observed within the diapirs to about 4 km of depth. A sketch of heat transfer within the salt dome and its surrounding is shown in Figure 2.9.

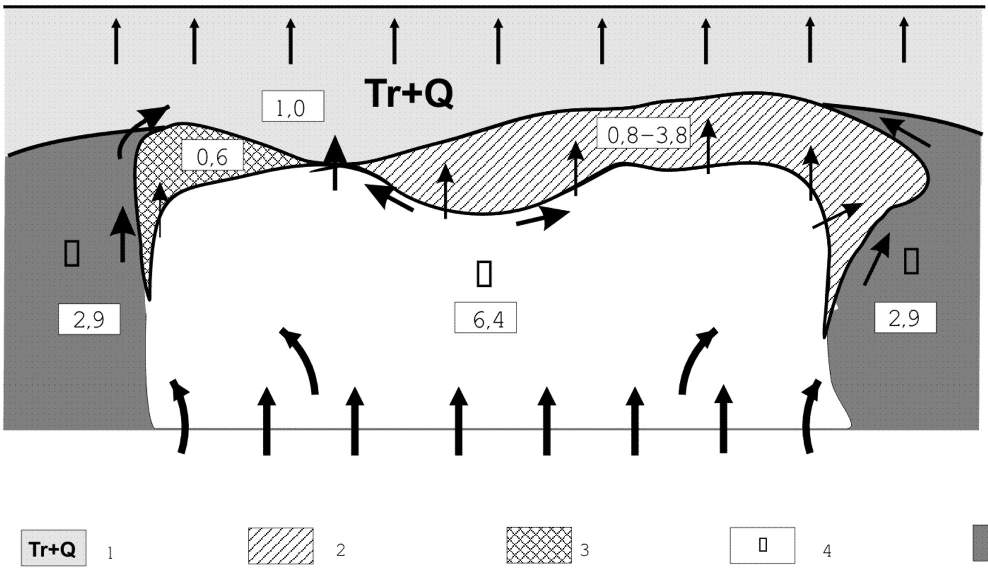


FIGURE 2.9: A sketch of heat transfer within the salt dome and its surroundings (Bujakowski [ed.] et al., 2003)
1. Tertiary and Quaternary sediments; 2. gypsum-anhydrite cap; 3. clay cap; 4. Permian (salt dome structure); 5. Jurassic. In rectangles - values of geothermal gradients, ºC/100 m

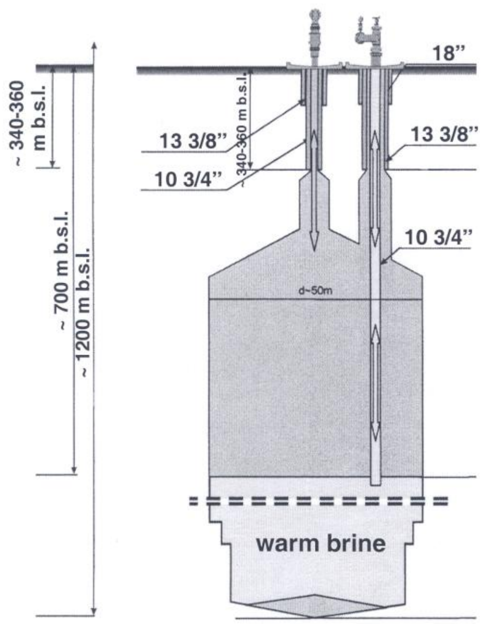


FIGURE 2.10: A sketch of a chamber formed as a result of salt brine underground leaching method and used for underground storage (based on Bujakowski [ed.] et al., 2003)

Salt from a few diapirs has been exploited on a great scale (table salt production and industrial applications) by the leaching method. It lies in the injection of water and undersaturated brine through the wells to a depth of some hundred to 1.2 km (at such depths, temperatures are higher by several degrees centigrade than in the neighbouring rocks). These fluids dissolve salt, and the produced brine is pumped to the surface. As the exploitation and leaching proceed, chambers are formed in the salt dome structure. In several cases, they are used for underground gas or oil storage (Figure 2.10). The brine on the surface reaches 28-30°C. It is a carrier both of the mineral substance (salt) for further processing, and for geothermal heat to the surface.

Recently, a numerical simulator TOUGH2 has been used for modelling selected salt diapir in view of usable thermal energy production (Pajak et al., 2003). The results show that a thermal capacity of 1 $MW_t$ can be yielded from the saline rooms at about 30$^o$C of the carrier. Thermal energy enclosed in the brine can be directly used for floor heating, swimming pools, and heating of soil in vegetable cultures. This energy can also be used indirectly through the heat pumps for space heating and domestic warm water preparation. What is important, for economic reasons, is that heat consumers should be as close to the energy source as possible. In some cases, potential consumers in small localities can be found near the diapirs – proper to develop small-to-moderate scale local geothermal heating systems.

Before starting thermal energy production from a specific diapir, an economic feasibility analysis has to be made. The subject on geothermal energy evaluation and possible production from salt domes will be continued.

## 8. CLOSING REMARKS

In Europe, geothermal energy is used predominantly in the space-heating, agricultural, and bathing sectors. Systems based on deep hydrothermal resources, as well as on shallow groundwater and rock formations, are successfully used. This variety of reservoir conditions and production methods proves the variety of possibilities in which geothermal energy can be used, adjusted to local conditions and needs. They are reliable and economically viable. Apart from natural reservoirs, it is also man-made reservoirs which are of scientific and practical interest. These “side-effects” of man’s activities, originally oriented to other objectives, create new possibilities. These few cases prove the versatile and universal character of geothermal energy recovery both through “traditional” and innovative schemes and technologies.

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## LECTURE 3

# GEOTHERMAL ENERGY DEVELOPMENT IN POLAND

## 1. INTRODUCTION

Poland is a country situated in Central Europe. It occupies an area of 323,500 km$^2$. The population is about 38 million inhabitants. The capital city is Warsaw, with some 1.8 million residents. Poland is a lowland country. The mean altitude is 174 m a.s.l. The Rysy peak in the Tatra Mts. (2,499 m a.s.l) is the highest point. The country lies in the temperate climatic zone with the result that the heating season lasts between 5 and 8 months per year. Owing to diversified geological structure, the country has numerous mineral resources (hard and brown coal, natural gas, copper, zinc and lead ores, halite, sulphur, phosphate rocks, building materials). Among important natural resources are also low-enthalpy geothermal resources. The country has a diversified landscape (mountains, sea, lakes), which abounds with many areas of great natural and environmental values. Forests cover about 28% of the territory. Different categories of protected areas include over 20 national parks.

Since 1989, Poland has been on its way to democracy and to a market-driven economic system. These fundamental social, political, and economical changes were initiated by the Solidarity movement. In May 2004, the country will join the European Union. The energy sector of Poland is based on traditional fossil fuels such as coal, oil, and gas. The first of them remains the main resource as the country has large coal reserves, taking one of the top places in the world. The interest in using renewable energy sources started to grow in the 1980s to 1990s. It was also inspired by the developed countries, including the European Union members, as well as the growing consciousness that energy policy has to be changed. This should result in the reduction of energy consumption, employment of economical and rational energy use methods, diversification of energy sources, and ecological benefits.

The results of research and estimations have proven that geothermal energy has the greatest potential at 90% among all renewable sources accessible in the country. Moreover, Poland is regarded to have one of the largest low-enthalpy geothermal potentials in Europe. The development of activities aimed at practical implementation of geothermal energy for heating purposes was initiated in the mid 1980s. Currently (2003), five geothermal space-heating plants are operational, while some other investment projects are underway. R&D studies of numerous geothermal issues, often of pioneer character, started to develop, and geothermal specialists were trained. Despite various difficulties caused by the political and economic transition period, typical of a number of Central and Eastern European countries, geothermal energy use started to develop gradually. Poland is in the beginning stages of development of geothermal energy use, therefore cannot yet be compared with other more advanced countries. However, the author hopes that some Polish geothermal solutions and experiences will be interesting and useful also for specialists from other countries.

## 2. GEOLOGICAL SETTING

Poland is situated in a specific part of Europe, where three main geostructural units building this continent meet. They are (Stupnicka, 1989; Figure 3.1):

- Precambrian platform of Northwestern Europe (occupying over half the total area of the continent);

- Palaeozoic folded structures of Central and Western Europe (Caledonian and Variscian), partly covered by the Permian-Mesozoic and Cainozoic sediments;
- Alpine system, running through Southern Europe from the Iberian Peninsula to the Caucasus Mts. In Poland, it is represented by part of the Carpathian range.

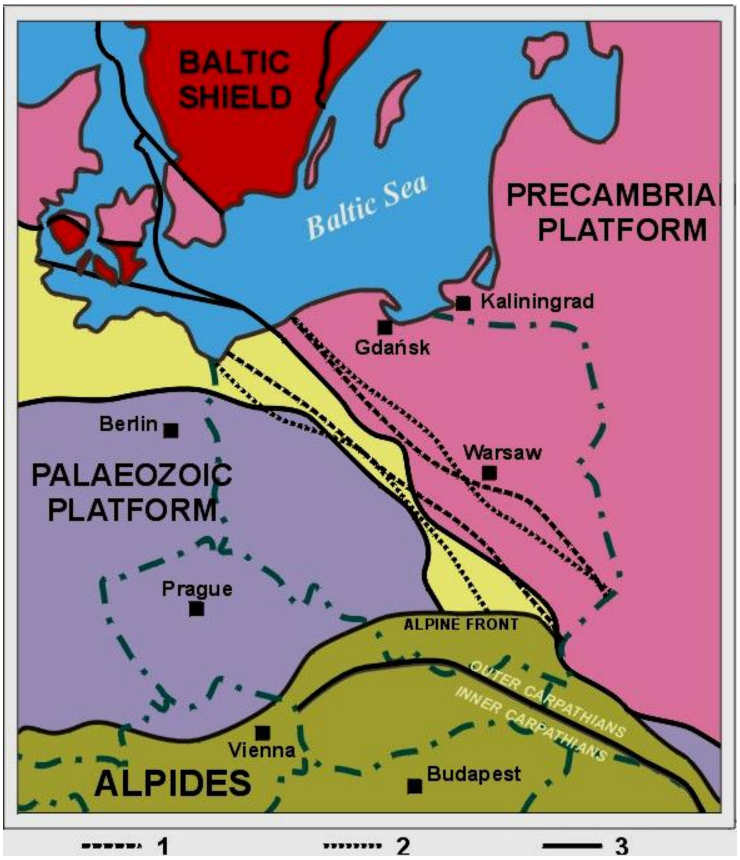


FIGURE 3.1: Geological setting of Poland within Europe
**1.** T-T zone; 2**.** Polish Trough; 3**.** Inter Cratonic Boundary

Poland is crossed by the Teisseyre-Tornquist tectonic zone (T-T zone). Being one of the most important and interesting geological structures in Europe, it separates two huge continental provinces: Precambrian platform of Northwestern Europe and Palaeozoic structures of Central and Western Europe.

Regarding lithological features of the aforementioned units, crystalline rocks prevail within the Precambrian platform (NE-Poland) and within the Sudetes region (SW-Poland) – the latter being a part of the Bohemian massif occurring mostly on the territory of the Czech Republic. Sedimentary rock formations dominate within the area framed by these two units and stretch from the Baltic Sea coast towards the central and southern part of the country built of the Polish Lowland and the Carpathians. The maximum thickness of sedimentary formations amounts to 7-12 km.

Large thicknesses and significant contributions of sandstones, limestones, and dolomites are characteristic of extensive areas built of sedimentary formations. These lithological rock types often have good hydrogeological and reservoir parameters. Therefore, they create favourable conditions for the occurrence of underground waters, including geothermal ones. Figure 3.2 shows an exemplary geological cross-section through Poland. It illustrates the large amount of sedimentary formations (predominantly of Mesozoic age), sometimes containing proven and potential geothermal water resources.

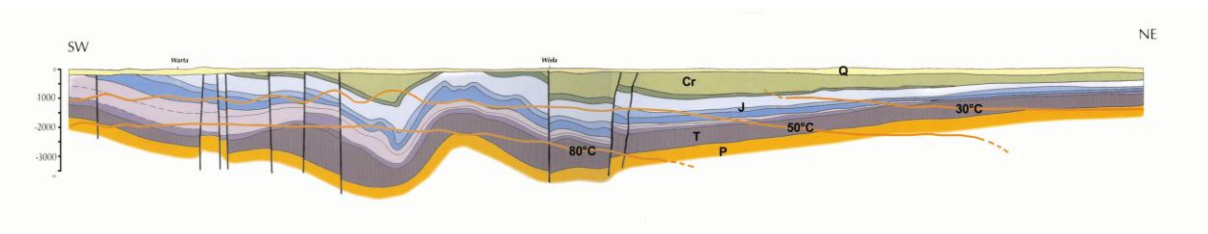


FIGURE 3.2: Geological cross-section through Poland showing a great share of Mesozoic sedimentary rock formations; some of them contain geothermal aquifers (Gorecki [ed.], 1995)

## 3. GEOTHERMAL CONDITIONS AND POTENTIAL

In general, Poland is characterized by low-to-moderate heat flow values. This parameter ranges from 20 to 90 mW/m2, while geothermal gradients vary from 1 to 4°C/100 m (Plewa, 1994). Thermal regime and geological conditions imply that Poland (similar to the prevailing part of continental Europe) mostly has low-enthalpy resources, predominantly connected with sedimentary formations.

A basic assessment of geothermal potential was conducted in the 1980s, when the interest in practical implementation of geothermal and other renewable energy sources started to grow. It was based on knowledge of geological structure of the country combined with comprehensive analyses and interpretation of data and results coming from several thousands of boreholes as well as geophysical, geological, and hydrogeological exploration and other works carried out for various purposes. These efforts resulted in evaluation of geothermal potential of Poland.

Three geothermal provinces have been distinquished in Poland (each of them being divided into several smaller units, called geothermal regions (Sokolowski 1993; Sokolowski [ed.]. 1995). They are built on extensive sedimentary formations (mentioned in the previous section) which cover about 250,000 km$^2$, i.e. 80% of the total area of the country and contain numerous geothermal aquifers (Figure 3.3):

- The Polish Lowland Province (ca. 222,000 km$^2$). The most extensive one with the geothermal aquifers related to sandstones and limestones (Triassic–Cretaceous);
- The Fore-Carpathians (ca. 17,000 km$^2$). The aquifers are connected with Mesozoic and Tertiary sedimentary formations;
- The Carpathians (ca.12,000 km$^2$). The aquifers are connected with Mesozoic and Tertiary sedimentary formations;
- The Sudetes region: geothermal aquifers are found in fractured sectors of crystalline and metamorphic formations (Dowgiallo,1976; Dowgiallo and Fistek, 2003).


FIGURE 3.3: Poland – division into geothermal provinces and regions (after Sokolowski, 1993); 1) Geothermal space-heating plants on-line; 2) Underway; 3) Spas using geothermal waters; and 4) Therapeutical facilities under construction in 2003.

Generally, at the depths from 1 to 4 km (technically and economically feasible at present), reservoir temperatures vary from 30 to 130°C. The TDS of waters change from 0.1 to 300 g/dm3. The proven geothermal water reserves, evidenced on the basis of flow tests from the wells, amount from several l/s up to 150 l/s. Static geothermal potentials of rock formations and waters were also assessed for particular provinces and regions (Sokolowski [ed.], 1995). The best conditions are found in the Polish Lowland Province and in the Podhale region (the Carpathians). Attention should be paid to numerous complexes of great regional range, and good hydraulic properties (potential and proven geothermal aquifers) in the Polish Lowland Province, owing to the lithology of the sandstones and carbonates making up the strata.

It should be pointed out that Poland has one of the richest low-enthalpy geothermal resources in Europe. Different but positive opinions are expressed by the professionals regarding the possible scale of their use. Considering reservoir parameters, technical factors and current prices of traditional energy carriers, economically viable geothermal facilities could be built on an area equal to some 40% of Poland's territory (Ney, 1999). This area is believed to be even bigger if another approach was adopted (Sokolowski, 1988; Sokolowski, 1993).

## 4. ENERGY POLICY OF THE COUNTRY AND PROSPECTS FOR RENEWABLE ENERGY SOURCES

The energy sector in Poland is based on traditional fossil fuels such as coal, oil, and gas. Hard coal remains the main source as the country has large reserves of this mineral, taking one of the top places in the world. Before the 1990s, energy was cheap. Frequently, the prices were below production costs, therefore had to be subsidized. However, in the 1990s, they started to grow and be more real as a result of political changes and introduction of the principles of a market economy. This fact also raised the interest in the potential and use of renewables in Poland which started to grow during the 1980s and 1990s. This was also inspired by the western countries, including the European Union members, as well as the growing consciousness that power policy had to be changed. to achieve a reduction of energy consumption, employment of economical and rational energy use methods, diversification of energy sources, and ecological benefits. Among available renewable energy sources in Poland are hydropower, biomass, wind, and solar energy. Geothermal has undeniably the greatest potential at 90% of total potential of all renewables.

The energy sector in Poland is in the process of transformations. This is a very tedious and costly social, economic, and political operation, hindering the development of the renewables. However, in the last ten or fifteen years, renewable energy sources have been the subject of research and various projects. They have begun to function in society consciousness and have found practical usage in some installations and plants. The EU member countries – which Poland will join in 2004, as well as other industrialised states, develop renewable energy technologies mainly in view of ecological concerns, and in order to reduce their dependence on imports of fossil fuel sources (particularly oil).

In Poland, current consumption of energy is still dominated by hard coal (over 60%); contrary to the global situation where other fossil fuels such as oil and natural gas have similar contributions as coal, i.e. each of these sources reaches some 20 to 34%. Poland has low consumption of renewable energy. In 2001, the market share of all RES, inclusive of waste energy was 6.1% while it did not exceed a level of 3.6% with waste energy excluded (Ney, 2003). These figures are beyond the average global (Table 3.1) and EU-countries' values.

The main document related to the whole sector of renewables in Poland is the Strategy of renewable energy resources development (Ministry of Environment, 2000). According to this document, the share of all renewable energy sources (RES), including geothermal, in energy production will oscillate around 7.5% in 2010 and 14% in 2020. These figures seem to be significant as compared to the current share of all RES in energy generation (ca. 3%), but inadequate for the country's potential and situation in many other European states. Among the main factors behind these low forecasts are the competitive prices of traditional fuels, insufficient financing, and weak institutional and law regulations.

TABLE 3.1: The structure of energy consumption in Poland and worldwide, 2001 (Ney, 2003)

| **Energy source** | **Poland** | | **World** | |
|---|---|---|---|---|
| | **A (%)** | **B (%)** | **A (%)** | **B (%)** |
| Coal | 62.3 | 65.62 | 22.0 | 24.7 |
| Oil | 19.6 | 20.7 | 34.3 | 38.5 |
| Natural gas | 12.0 | 12.6 | 21.2 | 23.7 |
| Nuclear energy | - | - | 5.9 | 6.6 |
| Renewable energy | 6.1[1)] | 1.1 | 16.6 | 6.5 |
| % | 100 | 100 | 100 | 100 |
| Energy consumption, million TOE | 93.8 | 89.8 | 10225.9 | 9125.9 |

A – Including estimated consumption of energy from renewable sources;
B – Including grid system hydropower only;
1) – Excluding waste energy penetration of renewable energy is 3.1%.

Within the sector of renewables itself, geothermal is still unappreciated since other RES are much more strongly promoted. Relatively high investment costs (especially when deep geothermal wells are to be drilled) are indicated as the main reason for such a situation. Moreover, the other cheaper solutions, both working and planned are often neglected and not mentioned even by the opponents.

On the other hand, as one of the main RES accessible in Poland, geothermal should also be promoted in view of Poland's pre-conditions connected with joining the European Union, as the country will be obliged to increase the use of renewables and reduce gas and dust emissions. Considering that geothermal is used in many locations chiefly for heating, it could contribute to a significant reduction of emissions caused by the burning of fossil fuels.

In the case of RES, there still exists no leading institution whose fundamental aim would be to support and coordinate all the activities. This is also one of the important obstacles to increase the share of renewables in the production of primary energy in Poland. On the contrary, there is a strong subsidiary system supporting development of the traditional power industry.

Progress in the development of geothermal as well as other renewables is anticipated due to the amended Energy Law binding power companies to purchase electricity and thermal energy obtained from renewable sources. This law also makes local administrations responsible for managing the heating market, including the use of local energy sources. In Poland, it is geothermal which can fulfil these conditions offering in many cases good reservoir conditions as well as several technical solutions, reliable supplies, and multiple options.

Nevertheless, the few legal acts introduced to date to facilitate the development of the RES sector, especially geothermal, are too general and insufficient. The appropriate economical and supporting instruments are still missing. It is expected that the new fundamental law concerning the renewables' management and development to be introduced soon will create more conducive conditions to wider geothermal development in the country.

As already mentioned, Poland is now beginning a greater use of geothermal. Despite all difficulties, geothermal energy develops gradually. Many solutions and the experience thus far are a good foundation for further development. In view of the accession to the EU, Poland will have better access to the international co-operation, EU funds for energy projects, and will be granted a greater share in RES. Among the most recent international initiatives is GEOFUND – a World Bank fund for minimization of geological risk connected with drilling first wells to be used for geothermal exploitation. Poland is one of the countries which should benefit from this fund.

## 5. MAIN DOMAINS AND METHODS OF GEOTHERMAL DIRECT USE

Reservoir conditions, ecological reasons, economic factors, and market demand determine current and future main types of geothermal applications in Poland:

- Space-heating;
- Agriculture (greenhouses, heated soil cultures);
- Drying (agricultural, industrial, wood products);
- Aquacultures (fish farming);
- Balneotherapy and recreation.

A key sector for developing geothermal energy use in Poland is space-heating. Wide-ranging application that would be adequate for the reservoir potential, market demand, and social interest would permit limiting reliance on traditional fuels, and eliminate the negative effects of such fuels being burnt. A huge potential lies in cascaded, multi-purpose and integrated types of uses that can be adapted to match a wide range of temperatures and purposes, making geothermal energy more effective, attractive and marketable. The temperatures of waters accessible for practical implementation cover a wide range, from several degrees to over 90ºC.

Several methods can already be applied for exploiting and extracting geothermal energy. This can be realized in the following forms:

- “Deep geothermics”: water (or heat) production from deep wells (up to 3-3.5 km);
- “Shallow geothermics”: water of low temperatures or heat produced from shallow wells extracted through heat pumps or borehole heat exchangers;
- Natural geothermal springs: 20-45°C water is used by seven spas for healing purposes.

Considerable prospects and expectations are linked with the adaptation of abandoned wells for the purposes of geothermal energy exploitation; several thousands of wells have been drilled within the country so far and some of them may serve for such aims. Such an approach may result in saving a considerable part of total investment costs. Another interesting option is recovery geothermal energy from underground mines in the Upper Silesia Coal Basin (Malolepszy, 1998; Malolepszy, 2000) or in other regions of the country. Another option offers geothermal energy extraction from salt dome structures.

The experience gained so far shows that the particular prospects for geothermal development in Poland greatly depend on the construction not only of large heating systems, but also of smaller installations that will work as multi-purpose, cascaded, distributed, or even integrated systems (i.e. combined both with traditional ones and other renewables as well).

## 6. GEOTHERMAL DIRECT USES – STATISTICS, 2003

Possessing a long tradition in geothermal bathing and balneotherapy dating back to the 13-14$^{th}$ centuries (Sokolowski et al., 1999; Lecture 1), Poland may still be regarded as a newcomer in the geothermal heating sector. The latter started to be developed in the last decade of the 20$^{th}$ century, and so far five geothermal space-heating plants have been launched.

As compared to the countries leading geothermal applications in Europe, this type of energy has been used on a limited scale mainly for heating, balneotherapy and bathing in Poland. In the middle of 2003 the total installed geothermal capacity amounted to 108.2 $MW_t$ while the heat production was about 455.5 TJ/a (Kepinska, 2003) (Table 3.2). The greatest contributors were five space-heating plants, in particular the plant in the Podhale region; 38 $MW_t$ and 150 TJ/a in 2002.

TABLE 3.2: Poland – geothermal direct uses 2003 (Kepinska, 2003)

| Type of use | Installed thermal power ($MW_t$) | Energy use (TJ/a) |
|---|---|---|
| Space-heating and warm water supply | 78.2 | 336.0 |
| Balneotherapy and bathing | 18.7 | 34.5 |
| Greenhouses, fish farming, drying | 1.0 | 4.0 |
| Other – extraction of $CO_2$, salts | 0.3 | 1.0 |
| SUBTOTAL | 98.2 | 425.5 |
| Heat pumps (estimated) | 10.0 | 80.0 |
| TOTAL | 108.2 | 455.5 |

Geothermal waters produced by natural springs or boreholes, with temperatures ranging from 20 to 62°C, are used for medical treatments in seven spas (Figure 3.3). The scope of geothermal bathing and balneotherapy is expected to be slightly increased, as some new projects were initiated in 2001-2002 (Section 7). This line of geothermal implementation and some historical highlights are more broadly discussed in Lecture 1.

## 7. GEOTHERMAL SPACE-HEATING PLANTS – AN OVERVIEW

### 7.1 General

As already mentioned, the space-heating sector represents the most important and prospective type of geothermal applications in Poland. Since 1992/93, five geothermal space-heating plants have been put into operation in various regions and localities in Poland (see Figure 3.3):

- The Podhale region (since 1992);
- Pyrzyce (since 1996);
- Mszczonow (since 1999);
- Uniejow (since 2001);
- Slomniki (since 2002).

One of the plants is situated within the Carpathian Province (the Podhale region), three are located within the Polish Lowland Province (Pyrzyce, Mszczonow, Uniejow) and one operates within the Fore-Carpathian Province (Slomniki).

As each of these plants is based on geothermal waters of different exploitation parameters, and serves different numbers of consumers, they operate on the basis of different schemes and vary considerably as far as thermal capacity and heat production are considered. Among them are plants with slight gas peaking only (Podhale); integrated plants with considerable gas contribution (Pyrzyce, Mszczonow, Uniejow); and plant integrating geothermal heat pumps with gas and fuel oil boilers (Slomniki). Three plants are based on well doublets and spent geothermal water is injected back to the aquifers while two of them are based on a single well and cooled geothermal water are used for drinking purposes (Table 3.3). Some other space-heating plants under realisation (2003) are described in Section 7.

TABLE 3.3: Poland - main data on geothermal space-heating plants, 2003

| Plant | Year of opening | Reservoir $T_{wellhead}$, TDS | Installed power ($MW_t$) | | Working scheme | Remarks |
|---|---|---|---|---|---|---|
| | | | Geothermal | Total | | |
| Podhale | 1992/93 | Carbonates, Triassic / Eocene 82-86ºC, TDS<3 g/l | 38 | 42 | Geothermal, gas peaking | Under extension – target 80 $MW_t$, 600 TJ, 2 production +2 injection wells |
| Pyrzyce | 1996 | Sandstones, Jurassic 61ºC, TDS 120 g/l | 13 | 48 | Integrated, geothermal + heat pumps + gas boilers | Completed - 2 production + 2 injection wells |
| Mszczonow | 1999 | Sandstones, Cretaceous 40ºC, TDS 0.5 g/l | 3.8 | 10.2 | Integrated, geothermal + heat pumps + gas boilers | Abandoned well adapted for geothermal use; Cooled water for drinking 1- well system, no injection |
| Uniejow | 2001 | Sandstones, Cretaceous 60ºC, TDS 8 g/l | 3.2 | 5.6 | Integrated, geothermal + gas boilers | Under extension; 1 well doublet |
| Slomniki | 2002 | Sandstones, Cretaceous 17ºC, TDS 0.4 g/l | 0.3 | 2.3 | Integrated, heat pumps + peak gas boilers | Shallow aquifer, low investment costs; Cooled water for drinking, 1-well system, no injection |

### 7.2 The Podhale region

The plant in the Podhale region (the Carpathians) was the first geothermal space-heating facility in the country. Its experimental stage was designed, constructed, and launched in 1987-1993 (Sokolowski et al., 1992). Since 1994, a large geothermal heating project has been under realisation (target capacity ca. 80 $MW_t$, heat production ca. 600 TJ/a (Dlugosz, 2003; Kepinska, 2000). By autumn 2001, the network supplied geothermal heat to over 220 buildings. In late 2001, a considerable part of receivers in Zakopane – the main city of the region (population 30,000, over 4 million tourists/year) were connected to the network. By 2005, geothermal will be delivered to the prevailing number of buildings in this city and the whole region. Heat supply will be based on geothermal, with gas being used at peak load. In 2002, the installed geothermal capacity was 38 $MW_t$ and heat production ca. 150 TJ (total ca. 190 TJ). The project forms a study case presented in Lecture 4 in this volume.

### 7.2 Pyrzyce

The space-heating plant in Pyrzyce (the Polish Lowland Province) was designed and realised in 1991-1996. It has been owned and operated by the limited-liability company "Geotermia Pyrzyce" established by the National Fund for Environmental Protection and Water Management, Pyrzyce County, Voiewodeship Fund for Environmental Protection and Water Management in Szczecin, and the State Treasury. The investment was financed by Polish and some foreign sources (own capital, loans, credits, grants).

The geothermal aquifer is situated within the Jurassic sandstones at depths of 1.4 to 1.6 km. The total thickness of reservoir formation is about 150 m, while the reservoir temperature is 64°C. Static water level stabilises 34 m below ground level. Water is produced with the use of submersible pumps. The maximum flowrate is 103 l/s of 61°C water. The TDS are 120 g/l. The aquifer is exploited by two production and two injection wells. The distance between them is 1.5 km.

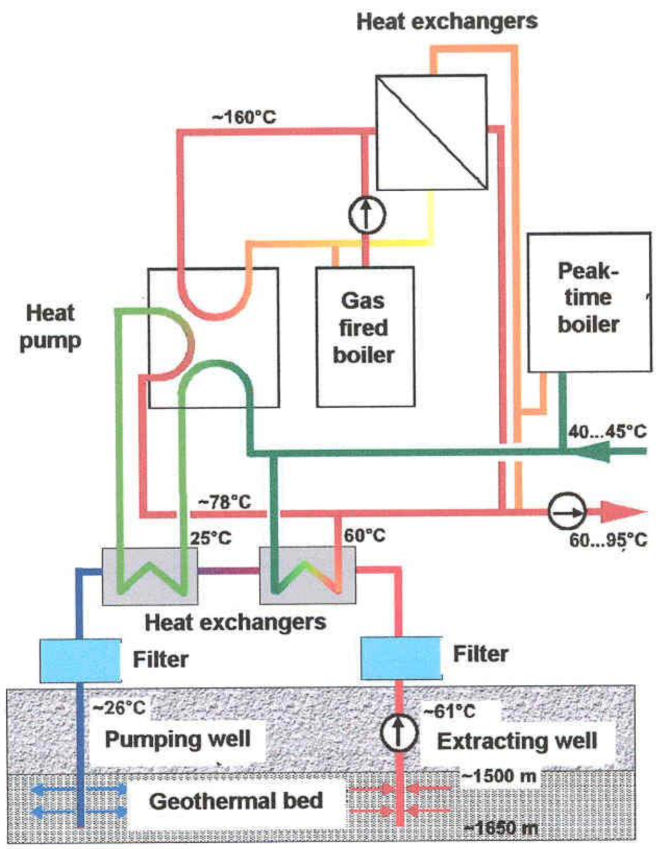


FIGURE 3.4: Pyrzyce – a sketch of a geothermal heating plant (according to Sobanski et al., 2000)

The plant's maximum installed capacity is 48 $MW_t$ including 13 $MW_t$ from geothermal water and 37 $MW_t$ from heat pumps and gas boilers. A simplified sketch of a plant is given on Figure 3.4. The plant supplies district heating and warm water to about 12,000 users out of the town's total population of 13,000, which is about 80% of the buildings in Pyrzyce. Along with construction of a new space-heating plant, a 15 km long new distribution heating network was built within the town. The network water parameters are 95/40°C (winter) and 60/45°C (summer) (Kulik and Grabiec, 2003).

In 2002, geothermal heat production was 95 TJ (Kepinska, 2003). The share of geothermal in total heat generation is about 60%, while the rest comes from gas boilers. The plant replaced 68 low-efficient, coal-based heating plants combusting about 30,000 tonnes of coal annually, and generating considerable amounts of emissions. Table 3.4 shows ecological effects achieved thanks to introduction of a geothermal-gas heating system in Pyrzyce.

TABLE 3.4: Pyrzyce – ecological effect achieved thanks to introduction of geothermal space-heating system (Kulik and Grabiec, 2003)

| Type of emission | Emission (tonnes/year) | |
|---|---|---|
| | Before geothermal system introduction | After geothermal system introduction |
| Dust | 240 | 0 |
| $SO_2$ | 660 | 0 |
| $NO_x$ | 38 | 0.5 |
| CO | 100 | 0.5 |
| $CO_2$ | 85,000 | 4,500 |

The main ecological and economical advantages of introducing geothermal energy for space- heating purposes in Pyrzyce can be briefly summarised as follows (Kulik and Grabiec, 2003):

- High efficiency of the heating system;
- Heat losses minimization;
- Quick reaction to the needs of the customers;
- Little staff;
- Adjustable production to the changing demand.

However, both the thermal capacity and heating network were oversized while project planning at the beginning of the 1990s. The current maximum capacity reaches approx. 27 $MW_t$. So a big decrease of thermal demand after the plant had been launched was caused by closing of several industrial factories, thermo-modernisation of buildings, installation of thermostatic valves and water-meters by individual heat receivers and, last but not least, by higher outside temperatures in the last several years. Relatively high costs of produced heat and its price are the result of partial utilisation of installed capacity and a large share of gas. On the other hand, owing to the lower heat consumption in Pyrzyce, the heating cost of 1 $m^2$ of a house is the same or slightly lower than the average cost of heating with the use of traditional boiler rooms in other localities across Poland.

In Pyrzyce, geothermal water is connected with sandstone formations. These types of rocks are characterised by the presence of clay minerals in a matrix. During water exploitation, these minerals cause some colmatation and plugging of well casings, filters, and reservoir formation. Also some grains of sandstones can be removed, washed out and transported by geothermal water, causing mechanical damages (cavitation). This phenomenon can be stopped by filters installed both in the production casing and in the surface instalment. Geothermal water itself has relatively high TDS, 120 $g/dm^3$, and in contact with the oxygen it forms a corrosive medium. Therefore, geothermal well casings are made of anti-corrosion substances guaranteeing 30 years of operation. Heat exchanger plates are made of titanium, whereas the geothermal transportation pipelines are of low sulphur or low-phosphorous carbon steel (less than 0.02%). During breaks in deep pump operations, nitrogen is pumped into the geothermal system to create the so-called nitrogen pillow, protecting against the access of corrosive oxygen into the system.

Geothermal water exploited in Pyrzyce contains several chemical components such as chloride, sodium, bromide, iodine, iron and manganese. It has healing properties and can be used for some treatments or bathing. Balneotherapeutic applications are planned as another prospective use, if financial sources to develop this line of activities are available (Kulik and Grabiec, 2003).

It should be noted that the Pyrzyce geothermal project assumed multi-purpose uses, i.e. agriculture, and bathing and balneotherapy. Unfortunately, only the heating part has been realized so far.

### 7.4 Mszczonów

Mszczonów is a town (population around 6,000) situated within Central Poland, some 40 km west of the capital city Warsaw. This is a very active town, attracting investors with its free economic zone. It takes care of the infrastructure and the use of pure geothermal energy in the municipal district heating system. In the future, the town and the whole county (similar to Uniejów, to be described later in the text) see their prospective economic success in the development of services, e.g. tourism for the inhabitants of the nearby big agglomerations, i.e. Warsaw and Lodz, and the use of geothermal waters for heating, recreation, and balneotherapy.

The heating plant in Mszczonów (the Polish Lowland Province) was launched in autumn 1999. Geothermal aquifers occur within the Cretaceous sandstones and sands at depths of 1602-1714 m. Maximum flowrate amounts to 60 $m^3/h$ of 40°C water. The TDS is low; 0.5 $g/dm^3$. Water is of high quality and fulfils the requirements of potable water. This feature enables the plant to operate one single production well only, without reinjection (Bujakowski, 2003). The well was drilled in the 1970s. In 1996-1997, it was reconstructed for geothermal water production, according to the R&D project co-financed by the Polish Committee for Scientific Research and the Mszczonów Municipality. The scientific supervision of the project has been conducted by the PAS MEERI Geothermal Laboratory. It was the first time in the country when an abandoned well was reconstructed and adapted for geothermal purposes. It is also worth noticing that the adaptation of an already existing well (instead of drilling a new one) significantly reduced investment costs.

The plant, with a total capacity of 10.2 $MW_t$, uses geothermal water both for heating and drinking. The heating part of the plant operates on the basis of an integrated system: the district heating water is heated to the required temperature by the heat extracted from geothermal water through a 2.7 $MW_t$ absorption heat pump fitted with gas boilers and a 0.6 $MW_t$ cooler. In the heating season, ca. 35% of a total heat supply comes from geothermal water. When cooled down in the heat pump, geothermal water can be used for drinking (TDS 0.5 g/l) and is supplied to the waterworks (Bujakowski, 2000a). A scheme of the geothermal plant in Mszczonów is given in Figure 3.5.

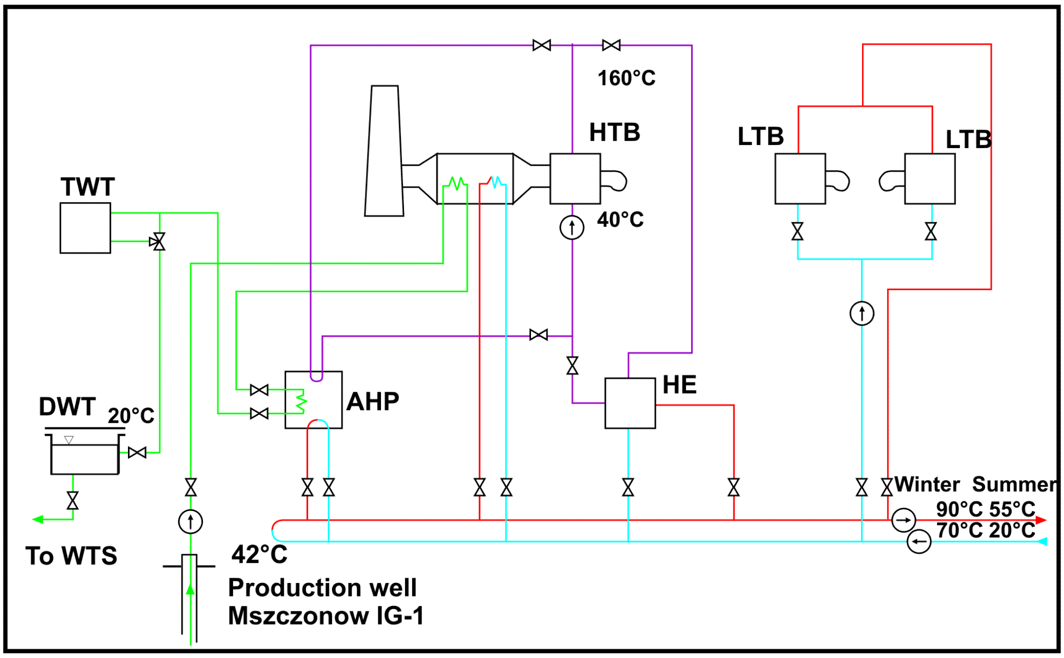


FIGURE 3.5: A scheme of the geothermal plant in Mszczonów;
APH – absorption heat pump; HE – heat exchangers; LTB – low-temperature gas boiler;
HTB – high-temperature gas boiler; DWT – cooled geothermal drinking water tank;
WTS – drinking water treatment station (according to Balcer, 2001)

The geothermal plant in Mszczonów replaced three traditional, low-efficiency space-heating plants. They had been based on coal-dust burning thus generating considerable amounts of emissions. The launch of the geothermal plant resulted in elimination of about 4,500 tonnes of coal annually. Harmful atmospheric emissions were reduced as follows: $SO_2$ by 100%, $NO_x$ by 82%, CO by 98%, $CO_2$ by 75%, soot and dust by 100% (Bujakowski, 2003).

According to the analysis conducted by 'Geotermia Mazowiecka' company (the owner and operator of the plant in Mszczonów), assuming identical work conditions and overheads, the costs of producing 1 GJ of heat in the gas boiler plant and in the coal-based plant are similar (gas being slightly more expensive) while in the case of the geothermal plant, the cost of producing 1 GJ was lower by 25% (Bujakowski, 2003). Recently, the Municipality of Mszczonów has initiated activities aimed at construction of swimming and recreational facilities based on geothermal water.

The geothermal plant in Mszczonów is one of the most original geothermal heating plants in Poland. This project has been conducted since 1996 in the following aspects (Bujakowski, 2003):

- Reconstruction of Mszczonów IG-1 well which had been drilled in the 1970s and closed in 1976; providing such a technical condition of the well which could ensure its long-term use;
- Accessing geothermal horizon; activation of water production and stabilisation of chemical parameters of produced water;
- Creation of a modern thermal energy source based on an absorption heat pump (using 40°C geothermal water as a low heat source);
- Optimal two-way use of geothermal water for heating and for drinking.

The underground part of the geothermal plant includes:

- Cretaceous sandstones hosting a geothermal aquifer;
- The Mszczonów IG-1 production well;
- Equipment installed in the well and its production facilities (wellhead, downhole pump, probes for measuring water level, temperature, pressure, flowrate, automatic system of data acquisition and processing).

The surface part of the plant includes:

- The wellhead equipment;
- The geothermal pipeline with a signalling and control system connecting the Mszczonów IG-1 well with the geothermal plant;
- A heating unit of peak demand low-temperature oil-gas-fired boilers (2x2.3 $MW_t$);
- A heating unit consisting of an absorption heat pump (2.7 $MW_t$) coupled with a high-efficiency oil-gas boiler;
- A DN 50-250 heat distribution network, with a total length of 3.7 km;
- An installation to utilise geothermal water in the existing municipal water-supply network.

Since the geothermal plant in Mszczonów is based on an over 20-year-old well reconstructed and adapted for the requirements of long-term warm water production, it is necessary to systematically monitor the well casing and other facilities – both old and added or installed during reconstruction works. Another specific problem is the sanding-up of the geothermal horizon. This process was first observed upon completion of the reservoir and its testing. Thus further systematic monitoring and measurements, as well as mineralogical and petrographical examination of the rock particles removed from the aquifer and carried out by water to the surface are being conducted. What also requires controlling and examination, is an analysis of the chemical composition of geothermal water, especially the content of chlorine ions. Increased concentration of this element may affect its usability for drinking purposes.

The mentioned issues are only a few of several problems of the Mszczonów geothermal system, production well and plant, and require constant control, further development of a specific methodology of testing, and monitoring. Such activities are being conducted by the PAS MEERI Geothermal Laboratory.

### 7.5 Uniejów

Uniejów (the Polish Lowland Province) is a small town (3,200 of population) situated in Central Poland. Thanks to natural conditions and landscape, the town and its vicinity are very attractive for the development of countryside tourism, especially for nearby agglomerations of Warsaw and Lodz – two of the largest ones in the country. An integrated geothermal-oil space-heating plant was put into operation in 2001.

This geothermal aquifer is situated within the Cretaceous sandstones at depths of 1900-2070 m. It belongs to the same regional formation which is being exploited in Mszczonów. The reservoir temperature is about 70°C. The maximum flowrate is 90 $m^3$/h of 68°C water in terms of self-outflow (4 atm static). The TDS are relatively low, at the level of 8 g/$dm^3$ (Kurpik and Cebulski, 2003).

Water is exploited in one doublet of the well system. The total installed capacity of the plant is 5.6 $MW_t$, including 3.2 $MW_t$ from geothermal and 2.4 $MW_t$ from peak oil boilers. The system is divided into two segments. One is a geothermal block consisting of a well doublet and heat exchangers, filters and the pumping system between the wells. The second one is the oil block comprising two low-temperature boilers using light furnace oil. The latter block heats the network water up to the required temperatures in the peak demand periods (Bujakowski, 2003) when the outside temperature is lower than -2°C. The heat distribution system includes a pipeline network made of pre-insulated pipes (total length of 10 km), with individual meters and valves.

In 2002, about 40% of heat consumers in the town were already supplied with space-heating and domestic warm water by this plant, while the number of connected clients amounted to 60%. The total heat production was ca. 20 TJ, including 15 TJ from geothermal water. So far, the system replaced 10 local coal-based boiler houses and 160 boiler units in single-family houses. The main pollutants generated previously by coal-burning for heating purposes were eliminated as follows: $SO_2$ – 31 tonnes/year; CO – 99 tonnes/year; $NO_2$ – 3 tonnes/year; dust – 33 tonnes/year. It resulted in improvement of air-quality in the town and its vicinity, as well as in considerable limitation of heavy metals contained in by-products generated by coal-burning and introduced to the environment. Works on connecting new consumers to the geothermal network are underway (Kurpik and Cebulski, 2003).

Owing to its valuable curative properties, geothermal water will also be used for balneotherapy and recreation. Medical investigations on healing features of warm water are currently underway. A geothermal swimming pool is going to be opened in Uniejow soon. The combination of geothermal balneotherapy and recreation as well as natural values and many historical monuments of this region of Poland, are anticipated to create very attractive weekend and holidays tourist offers. It should give new possibilities for local economical development, and new places of employment.

### 7.6 Slomniki

Slomniki (the Fore-Carpathians Province) is a small town (5,000 population) situated in southern Poland. In late 2002, a moderate–scale heating system based on heat pumps was launched. It was an outcome of a project prepared, conducted, and supervised by the PAS MEERI Geothermal Laboratory in cooperation with the local municipality. Currently (2003), the plant is in the initial phase of operation.

Geothermal water is connected with shallow (ca. 305–309 m) Upper Cretaceous (Cenomanian) sandstones and sandy limestones (Figure 3.6). This formation has relatively high water flowrates, in the same cases self-outflows are recorded. On the other hand, in Slomniki and adjacent areas, due to shallow location at depths not exceeding several hundred meters (up to 200-800 m), the reservoir temperatures are low (up to 40°C, sometimes even less than 20-25°C). However, owing to other reservoir properties, this formation has been a subject of R&D works as a potential base for moderate-scale space-heating systems using heat pumps (Barbacki and Uliasz-Misiak, 2003). The project which has been underway in Slomniki is intended to test and implement such a scheme, much cheaper and easier to run than the so-called "deep geothermics".

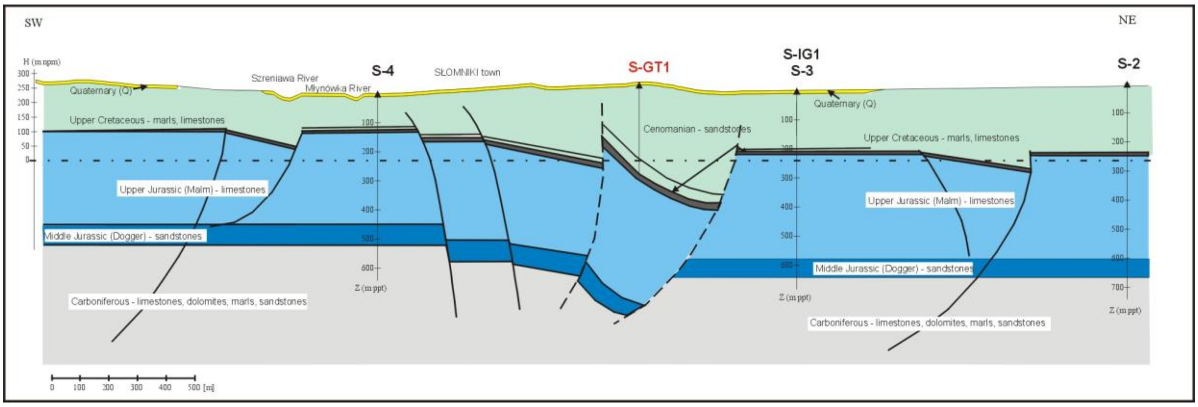


FIGURE 3.6: Geological cross-section through Slomniki area, S-Poland

The system in Slomniki works as an integrated one: maximum 53 $m^3$/h of 17°C water produced from Cenomanian sandstones and sandy limestones – heat pumps – gas and fuel oil boilers (Figure 3.7). The total installed capacity amounts to 2.3 MWt, including 0.3 $MW_t$ from geothermal water being a low source for heat pumps, while the rest comes from gas and fuel oil boilers. Currently the system supplies the school building and two blocks of flats. When the outside temperature is above - 5°C, the heat delivery is based on geothermal heat pumps; and if it is lower than this value, the system is switched into gas and oil boilers. After cooling down in heat pumps, geothermal water is sent to the water works as drinking water (TDS 0.4 g/$dm^3$). In the near future, several other public buildings and a residential housing estate will be connected to the system (Bujakowski, 2003).

The case of Slomniki is a good example of moderate – scale installation integrating a low-temperature geothermal energy source and traditional fossil fuels. It is characterised with relatively low investment costs therefore it is possible to be followed by other localities or even individual investors.

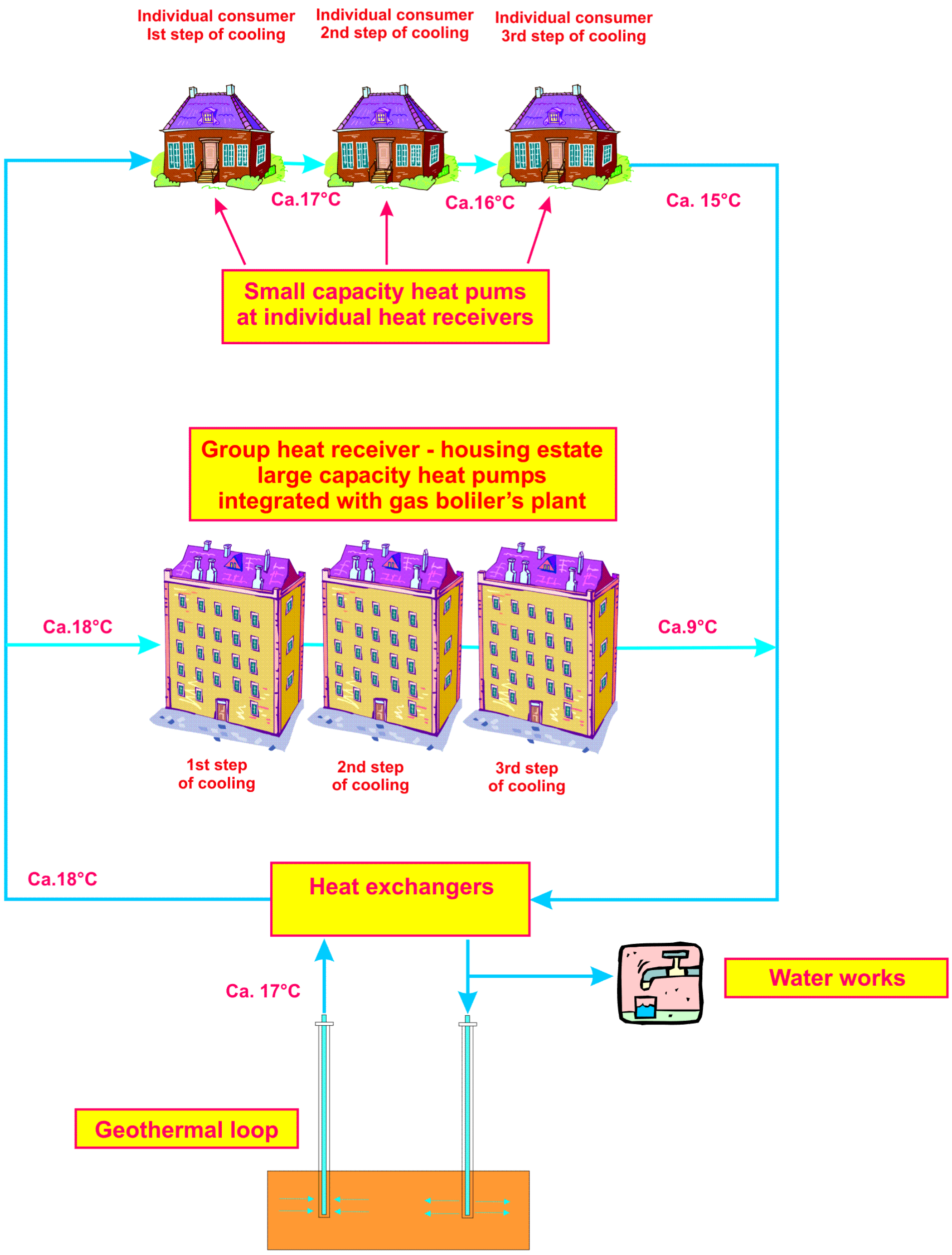


FIGURE 3.7: A sketch of a geothermal plant in Slomniki

### 7.7 Geothermal heat pumps

Interest in using heat pumps in the geothermal sector has been slowly but gradually rising in the country, although the progress can not yet be compared with the leading European countries, such as Sweden, Switzerland or Germany. Heat pumps have been working in three geothermal space-heating plants (Table 3.3): in Pyrzyce (two pumps of 20.4 $MW_t$ total capacity); Mszczonow (2.7 $MW_t$); and in Slomniki (0.32 $MW_t$). The first heat pump, using as a low heat source ventilation air from a coal-mine with a temperature of 16-19°C, was installed in 1997 in the Upper Silesia Coal Basin. Currently, it is not in operation after the mine was closed. However, practical implementation of geothermal heat contained in ventilation air and warm waters pumped out from the underground mines forms a very prospective option, more broadly discussed in Lecture 2. Besides, medium- and small capacity heat pumps based on ground or groundwater are installed for individual consumers and office buildings. Very roughly, one can suppose a number of at least 700-1000 such pumps within the country (installed capacity ca. 10 $MW_t$ and heat production ca. 80 TJ/a). The interest in using heat pumps should increase, especially when the home-made devices which are cheaper than the imported ones will become available on the market.

## 8. GEOTHERMAL INVESTMENTS UNDERWAY (2003)

Different stages of four geothermal investment projects were underway in the autumn 2003 (Figure 3.3). Some of them concerned the continuation of projects which had already been partly on-line, while some of them were new ones.

**The Podhale region** (the Carpathian Province**):** The regional district heating system was planned to be finished in 2005. In Zakopane – the main city of the region, a large geothermal bathing centre has been in construction (see Lecture 4 for details);

**Uniejów** (the Polish Lowland Province): Works going on connecting new heat consumers. Geothermal swimming pool – a part of a future aqua-park, was expected to start in autumn 2003. The R&D on curative features of geothermal water were being conducted, which had to be followed by the construction of a balneotherapeutical centre;

**Duszniki** (the Sudetes region): So far, ca. 19°C water discharged by one geothermal spring and cold mineral water were used for medical purposes. Recently, a deep (1695 m) well was drilled, and over 30°C water was obtained. Because of highly curative features, it will be implemented for healing treatments and a thermal pool, thus increasing the curative capabilities and scope of services offered in this very popular spa (Dowgiallo and Fistek, 2003);

**Stargard Szczecinski** (the Polish Lowland Province): Construction of a geothermal space-heating plant in the town with a population of 75,000. The project has been conducted by the limited liability company 'Geotermia Stargard'. In 2001-2003, a deep production (2672 m) and deviated injection well (2960 m) were drilled (the latter being the first directional geothermal well in Poland). The surface distance between the wells is 8 m, while the downhole distance within the reservoir is 1500 m (Kozlowski and Malenta, 2002). The aquifer is situated within the Jurassic sandstones. During the initial well tests, outflow of 87°C water was obtained.

In Stargard Szczecinski, there is no need to construct heating distribution networks and related facilities, as this city possesses large and well-functioning instalments. Therefore, the project focuses on constructing a geothermal base load plant which will consist of a geothermal doublet and heat exchanger units (Figure 3.8). Geothermal heat will be extracted by heat exchangers (total capacity 14 $MW_t$), and then it will be sold to the existing coal-fired municipal district heating plant (total capacity 116 $MW_t$) serving about 75% of the local population. This plant will distribute geothermal heat to the consumers in the town through the existing 37 km long heating network and over 250 heat exchanger substations. In such a way, a considerable part of coal burning will be eliminated by geothermal energy (Kozlowski and Malenta, 2002).

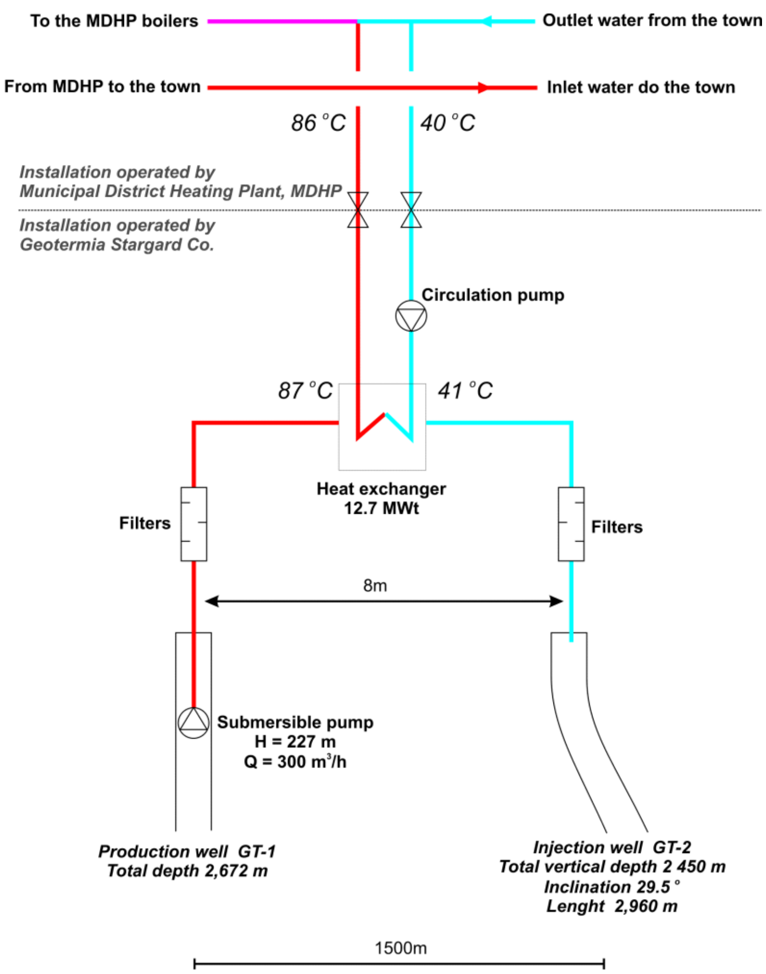


FIGURE 3.8: Stargard Szczecinski - a sketch diagram of a geothermal plant (Kozlowski and Malenta, 2002)

In 2001, the existing municipal heating used over 45 000 tonnes of fine coal while the amount of related emissions were as follows: $SO_2$ – 466 tonnes; CO – 304 tonnes; $CO_2$ – 98,747 tonnes; $NO_2$ – 182 tonnes; dust – 255 tonnes; soot – 2 tonnes (Kozlowski and Malenta, 2002). The geothermal plant is expected to be put into operation in December 2003. It is planned that about 300 TJ/a of geothermal heat will be delivered to the municipal district heating network. Geothermal is assumed to fully cover the heat demand for preparation of tap water in the summer period; while during the heating season, geothermal will be supported by heat produced by the existing coal-fired municipal plant. Geothermal heat production will make it possible to reduce the yearly consumption of coal by 33% (15,194 tonnes/year) as compared to 2001.

During project preparation, special attention was paid to economical aspects to obtain low production costs per geothermal heat unit and its price, therefore making it competitive with the heat received so far by burning coal – the basic and the cheapest energy source. The heat sales price was negotiated at a level equal to 3.8 USD/1 GJ (Kozlowski and Malenta, 2002).

## 9. RESEARCH IN PROGRESS AND PROJECTS PLANNED

It should be pointed out that apart from the plants on-line and investments under realization, many assessments and projects on geothermal use have been prepared over the last decade for many regions, towns and facilities in Poland. They concentrate on geothermal heating, mainly in the Polish Lowland Province, which is characterised by good geothermal parameters suitable for this type of use (Ney and Sokolowski, 1987; Sokolowski 1993; Górecki [ed.], 1995: Hurter and Haenel [eds.], 2002). When new projects are prepared, the experience of the existing operations is taken into account to minimise the risk and investment costs and to make the projects profitable in specific circumstances also with the traditional fossil fuels and other local renewables in mind.

The research, R&D works, elaborated projects, and activities planned include different schemes and solutions:

- The adaptation of abandoned wells;
- Geothermal heat pumps;
- Cascaded and multi-purpose systems;
- Integrated and distributed energy systems.

These solutions provide particular chances for geothermal development in Poland by reducing investment costs, increasing the effectiveness of investments, and expanding the market. The area which shows great promise for development is bathing and recreation, especially if new facilities would be constructed as a part of the multi-purpose or space-heating oriented projects. Apart from installations based on geothermal energy, systems integrating geothermal with other renewables and even traditional energy carriers are taken into account, depending on local conditions.

However, as given in Section 4, the level and conditions of financing of many innovative and feasible projects are insufficient, particularly from the Polish sources, which is the main obstacle to a wider geothermal use in the country. One should also mention insufficient support by the governmental policy, which could encourage and promote such activities. Despite this, the plants in operation, investments, research, and projects have an impact on the gradual development of geothermal and its social acceptance.

## 10. INNOVATIVE GEOTHERMAL CONCEPTS AND THEMES

Some innovative geothermal concepts and themes have been initiated in Poland:

- Geothermal heat recovery from underground mines;
- Research of thermal conditions of salt-dome structures and evaluation of their practical implementation as geothermal heat sources.

Recovery of geothermal heat from underground mines is a specific but prospective subject. This idea still awaits practical realization. Research and project studies are continuing on this subject (Malolepszy, 1998; Malolepszy, 2000; Bujakowski, 2001). Salt diapirs – specific tectonic structures formed of Permian saline formations (Bujakowski [ed.] et al., 2003; Pajak et al., 2003) are a subject of the newest research. Such structures are present in the Polish Lowland Province and in other European countries, e.g. Germany. These two issues are discussed in more detail in Lecture 2.

Recently, the possibility of power and heat co-generation using binary schemes has been considered. It may be based on over 90°C waters which were tapped in some deep wells (over 3 to 4 km) or are expected to occur especially within the Podhale region (the Carpathian Province) and within the Polish Lowland province.

## 11. CLOSING REMARKS

Poland is a country where geothermal has been used on a limited scale for space-heating for a dozen years. Although lacking in spectacular geothermal manifestations, the country has a considerable low-enthalpy potential, placing it among the most prospective countries in Europe. Geothermal energy, similar to other renewables, develops in the shadow of the traditional power industry, the coal industry in particular. More favourable legal regulations, as well as economic and fiscal incentives, should be introduced. They would be a tool for the promotion of geothermal energy and, first of all, the creation of equal opportunities for geothermal and traditional fuels – a starting point for the rational energy policy.

Geothermal seems to gain a significant share particularly in the local heating market in many regions, which will mitigate the level of emissions from the burning of fossil fuels both at a local and regional scale. A high potential for geothermal energy use also exists in the agricultural and food sector, aquaculture, balneotherapy, and recreation, which can be realized in cascaded or multi-purpose schemes.

Experiences thus far indicate that for further successful progress in geothermal energy implementation, it is necessary to limit investment costs so as to make geothermal energy more competitive and marketable than the heat obtained from other sources. With this in mind, emphasis is placed on the construction and planning not only of large facilities based on deep wells, but also of smaller installations which make use of the existing wells, shallow ground and aquifers, and which can work as cascaded and/or integrated systems. In operational geothermal plants, the cost of heat production and sale are lower than for fossil fuels, e.g. gas, oil and electricity, and comparable with the costs for coal (the cheapest but the most contaminating energy source in Poland). It is worth noting that geothermal instalments and the heat itself are heavily taxed.

Geothermal facilities in use or under construction will surely provide further arguments for the feasibility and profitability of geothermal energy, thus facilitating the raising of funds for research and project delivery, and helping to elevate geothermal energy to the more important role in the renewable energy sector and in Poland’s sustainable development, which it undoubtedly deserves.

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## LECTURE 4

# THE PODHALE GEOTHERMAL SYSTEM AND SPACE-HEATING PROJECT POLAND – CASE STUDY

## 1. INTRODUCTION

In Europe, many low-enthalpy geothermal systems have been known and exploited for years. There are also a number of new systems being studied in detail and put into use. One of them is the Podhale system in Poland. Since the 1980s, this region has been the subject of intense research works and activities oriented towards geothermal energy implementation for space heating and other uses. Here, an experimental geothermal plant was put into operation – the first in Poland; and successively a great regional heating system has been developed (planned to be terminated in 2005). It is the place of the first geothermal experience, and the resulting ecological effects. Podhale has a tutorial meaning for the other geothermal space-heating plants in Poland. It is also an important exemplary case for geothermal projects in the Central and Eastern European countries, arousing interest both in the home country and abroad.

The project involved significant progress in geological, reservoir, and thermal exploration, and research in the Podhale region that required many specialized investigations and modern techniques. Many Polish scientists and specialists including also some former UNU-GTP Fellows have been engaged in this project.

More than ten years of project development brought many results of both cognitive and practical meaning for the proper long-term exploitation of the geothermal reservoir and the heating network operation. So far, results (some of which are outlined in this paper) prove that it belongs among the most interesting and prospective systems in Europe, in respect of reservoir conditions and utilisation.

This paper gives comprehensive review of the most crucial geological, reservoir and thermal features of the Podhale system, followed by the main assumptions of the geothermal utilisation project. Basic technological, financial, and organisational issues, main successive stages of a geothermal space-heating project, as well as the present state of its realisation and main ecological effects and benefits achieved so far are highlighted. Some results of the most recent special investigations of the sector being currently exploited are presented. These enable the understanding of the complex history of the factors controlling the geothermal reservoir, its proper current exploitation, and development planning.

## 2. THE PODHALE REGION – GENERAL INFORMATION

The Podhale region is located in southern Poland, within the Inner Carpathians. Its area amounts to about 1000 km$^2$, with a population of about 150,000. In the south, it borders Slovakia - through the Tatras, the only mountains of Alpine character in Poland with the highest peaks of Rysy (2499 m a.s.l.) and Gerlach (2655 m a.s.l.). The central part of the Podhale region is occupied by the Podhale Basin – the structure, which contains geothermal reservoirs.

Podhale is well known as a very popular tourist, sport, and recreational destination in Poland, which is visited by over four million tourists annually. It belongs to one of the most valuable regions in Europe due to the following features:

- Variety of landscape and geological structure;
- Unique flora and fauna (four Polish national parks exist there, including the Tatra National Park being joined to the Worldwide Man and Biosphere Reservation System, M&B);
- Climatic and tourist value (the centre of winter sport and alpinism, with a number of boarding houses and hotels, a venue of national and international winter sports competitions);
- Vital, rich folk culture and tradition cultivated by local highlanders;
- Large resources of geothermal waters characterized by favourable parameters.

On the other hand, Podhale has been affected by extensive pollution of the natural environment caused by the burning of large quantities of hard coal for heating (heating season lasts 8-9 months). Therefore, the project of a regional geothermal heating network having been realised since 1987 is of fundamental significance to stop further degradation of the Podhale ecosystem, conduct sustainable management of the environment, and preserve it for future generations. It will help to improve the standard of living of people inhabiting the area, and multi-purposed implementation of geothermal energy will bring about new opportunities for the local economy.

## 3. GEOLOGICAL SETTING AND EVOLUTION

In the Podhale region, the two main parts of the Carpathian orogeny exist - the Inner and the Outer Carpathians. They are fragments of the mountain chains that were folded during the alpine orogeny (Cretaceous–Tertiary). Within them, the following geological units have been distinguished (Figures 4.1 and 4.2):

- The Inner Carpathians: the Tatra Mountains, the Podhale Basin, and the Pieniny Klippen Belt. They are the constituents of the Podhale geothermal system and each of them plays its own specific role within it;
- The Outer Flysch Carpathians: these structures extend north of the Pieniny Klippen Belt and have no direct connection with the Podhale geothermal system.

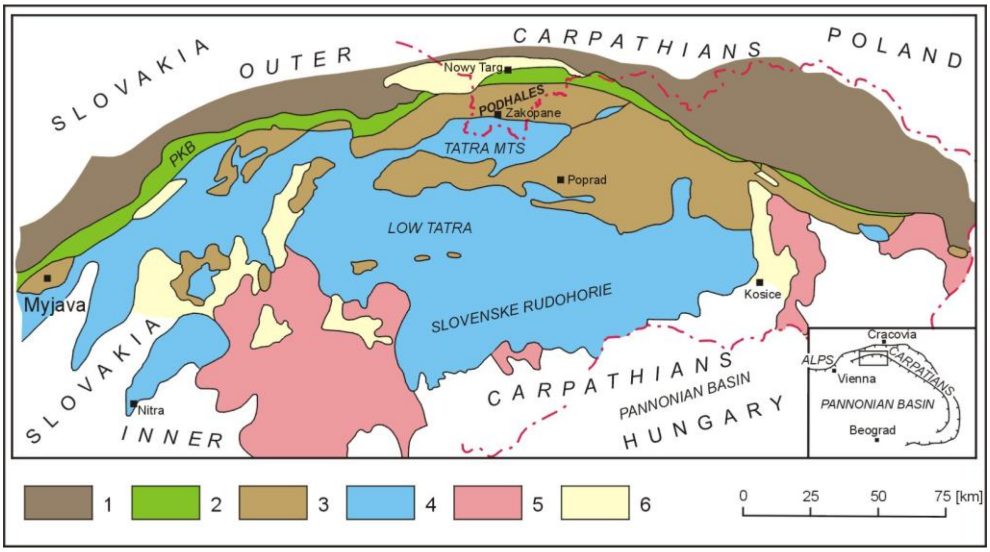


FIGURE 4.1: Location of the Podhale region within the Carpathians
1. Outer Flysch Carpathians; 2. Pieniny Klippen Belt; 3. Inner Carpathians Palaeogene depressions (containing geothermal aquifers); 4. Palaeozoic-Mesozoic massifs of the Inner Carpathians; 5. Neogene volcanites; 6. Neogene sediments in intra-montane depressions

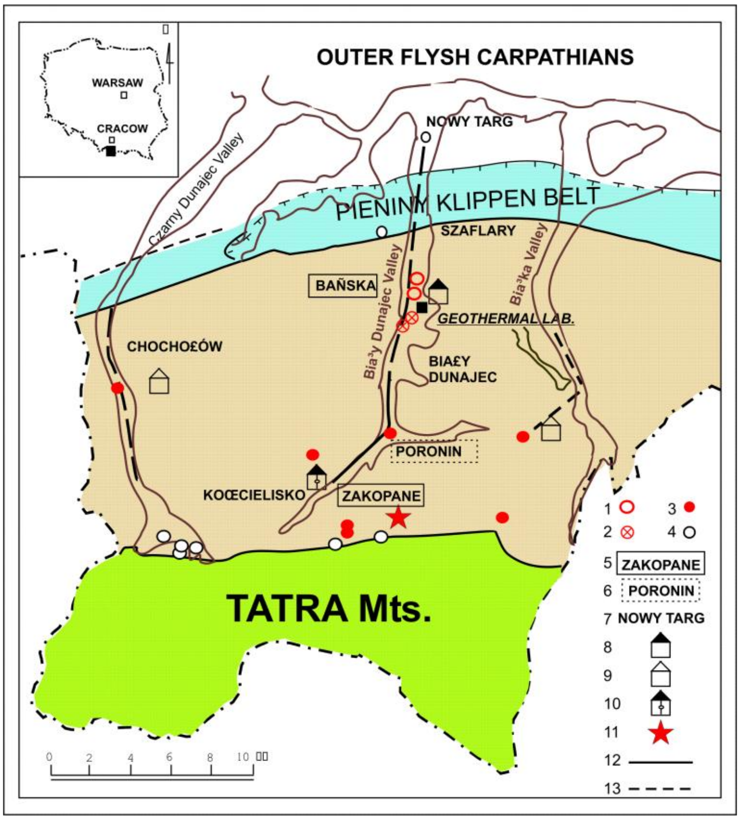


FIGURE 4.2: Geological sketch of the Podhale region, location of geothermal wells and geothermal heating network under construction
1. geothermal production well; 2. geothermal injection well, 3. well not in use; 4. other wells; 5. locality with geothermal heating system on-line (2003); 6. localities under connection to geothermal heating network; 7. localities planned to be geothermally heated; 8. geothermal base load plant; 9. geothermal heating plants planned; 10. central peak load plant; 11. warm spring (existing until 1960s); 12. main transmission pipeline; 13. transmission pipelines planned

**The Tatra Mountains** are built of a Palaeozoic crystalline core (igneous and metamorphites) and sedimentary rocks. The latter form a number of overthrusted tectonic units (Lower Triassic–Middle Cretaceous) and act as a cover of the Palaeozoic core. These units consist mainly of limestones, dolomites, sandstones, marls and clays. They continue to the north, creating the basement of Palaeogene formations that fill the Podhale Basin. They form also the reservoir rocks for geothermal water. The Tatra Mts. massif is regarded as a main recharge area for geothermal aquifers.

**The Pieniny Klippen Belt** is built of Mesozoic and Palaeogene sediments forming several tectonic units. Regional dislocations separate this structure, usually not exceeding several hundred metres in wideness, from the surrounding units: the Podhale Basin in the south and the Outer Carpathians. The Pieniny Klippen Belt is a relict of the subduction zone of the African and North-European continental plates being active during the alpine orogenesis (since Jurassic through Cretaceous till Neogene). At present, this extremely complex structure is a very long but narrow belt. It stretches almost 800 km from Vienna (Austria) through Slovakia and Poland to Romania ranging from only several hundreds of meters up to 3-5 km in wideness within the area of Poland. The Pieniny Klippen Belt forms the northern impermeable boundary of the Podhale geothermal system.

**The Podhale Basin** is the Polish part of the extensive Inner Carpathian Palaeogene basins (troughs) located mostly within Slovakian territory (where numerous geothermal systems are found, some of them being exploited for bathing or heating purposes (Fendek and Franko, 2000)). Its area within Poland amounts to about 475 km$^2$. The Basin was formed in the Palaeogene as an effect of irregular, block uplift of the Tatra Mts. and the Pieniny Klippen Belt. Its basement is composed of Mesozoic formations (that contain geothermal aquifers) outcropping on the surface mostly in the Tatra Mountains. The profile of the Palaeogene formations that fill the basin includes conglomerates and nummulitic limestone (Middle Eocene) of variable thickness (0–350 m), and the Podhale flysch (Upper Eocene–Oligocene) is composed of shales, mudstones and intercalations of sandstones (reaching the maximum thickness of 2.5–3 km).

The Podhale geothermal system – a subject of this lecture – occurs within the Podhale Basin. In the south, it borders the Tatra Mts., its main recharge area; while from the north it is limited by the Pieniny Klippen Belt acting as an impermeable barrier. A geological-thermal cross-section through the Podhale region is shown on Figure 4.3.

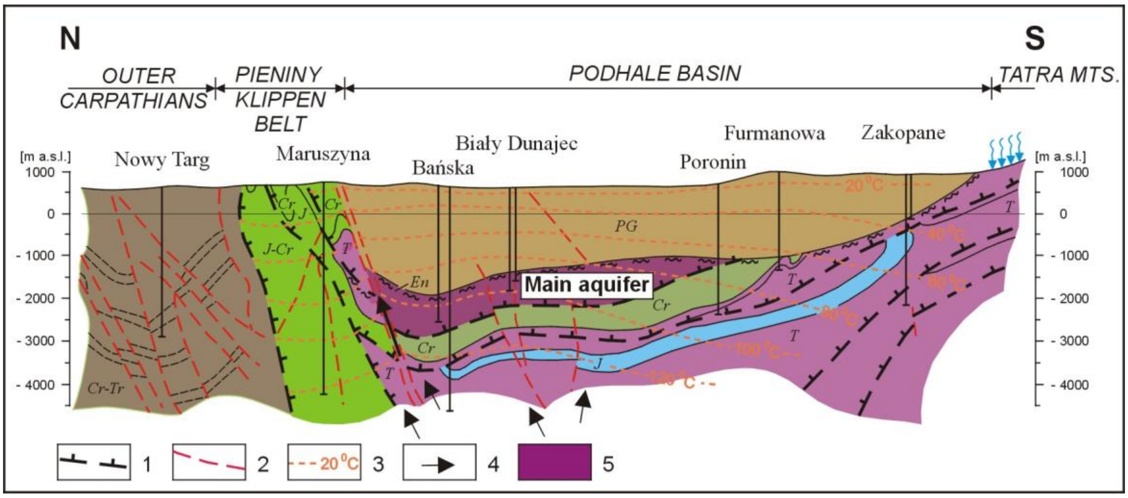


FIGURE 4.3: Geological – thermal cross-section through the Podhale region (geology based on Sokolowski, 1993, updated)

The Podhale system is characterised by long and multi-stage geological evolution (Triassic-rec.). It embraces:

- The rock sedimentation (Triassic-Cretaceous, Palaeogene);
- Alpine movements: in that overthrusting and tectonic transport of Mesozoic units to ca. 150 km during Upper Cretaceous-Paleoqcene and subduction in the Pieniny Klippen Belt zone;
- Vertical movements and compression in the Neogene. They resulted in brecciation of rocks, formation of faults and fractures. This had a decisive influence on the past and present conditions of waters and heat circulation, water chemistry, etc.
- The erosion and denudation processes played an important role too, in particular weathering and karst processes in the early Tertiary (before the Middle-Eocene transgression and covering the Mesozoic rock by the Palaeogene flysch). They affected the exposed Mesozoic rocks (particularly Triassic carbonates are very supple to such processes) forming numerous fractures and caverns that improved the reservoir properties of rocks.
- Starting from the Neogene, the karst processes have developed in the outcrop zone of the carbonaceous Mesozoic and Middle Eocene rocks, influencing the conditions of water circulation and inflow into deeper parts of the system.

It follows from the analysis of the geological evolution of the described region that in the past there used to exist different geological and reservoir conditions (water recharge and inflow, pressure, temperature distribution, fluid chemistry) from the present ones being created during the Neogene and Quaternary.

## 4. MAIN FEATURES OF THE PODHALE GEOTHERMAL SYSTEM

### 4.1 General

The Podhale geothermal system is built of two basic units: Mesozoic (Triassic-Cretaceous) and Tertiary (Palaeogene) formations (Figures 4.2 and 4.3). Older formations (Palaeozoic) are expected to underlie the Mesozoic series. The Mesozoic rocks have a typical alpine structure. They form numerous nappes and scales overthrusted and folded during the Upper Cretaceous-Palaeocene orogenic period. Tertiary carbonate transgressive series (0-350 m in thickness) and a thick flysch formation (2.5-3.2 km) were deposited *in situ* on the basement of the overthrusted Mesozoic units. At present, they form a structural depression (trough). The rocks, which built the Podhale system, underwent long and complex geological evolution. The Middle Triassic rocks are ca. 235 Ma, while the sedimentation of the Middle Eocene carbonates started ca. 50 Ma ago, and the Podhale flysch - 45 Ma ago. Their common history as a geothermal system began after the flysch had been deposited, ca. 22 Ma ago.

In this paper, the main features of the geothermal system being important for its exploitation for heating purposes were compiled on the basis of the results of the numerous investigations thus far, namely: geological and geophysical survey, hydrogeological, reservoir, temperature, and chemical in situ and laboratory tests. Well logging and reservoir tests in more than 10 deep geothermal wells drilled within the area of question provided the principal data. Some other special geothermally-oriented investigations having been carried out since the 1980s brought essential results.

Current exploitation of the Podhale system and further heating project investments have been accompanied by the investigation and monitoring of the discussed system. They aim at detailed recognition of this structure and assuring proper geothermal water exploitation and project planning. The research involves both classical and innovative methods. Some results of such research focussing on the exploited sector of the Podhale geothermal system are presented in Appendix 1.

### 4.2 Reservoir rocks

Several geothermal aquifers have been found within the Mesozoic basement of the Podhale Basin. Reservoir rocks for geothermal waters are mainly Triassic carbonates, and sometimes Jurassic sandstones and carbonates (Figure 4.3). The particular aquifers are separated from the top and bottom by semi-permeable Jurassic and Cretaceous series (mudstones, siltstones, shales). They isolate the aquifers and limit the water flow, which is driven mostly by the planes of faults and fractures. The most favourable and prospective geothermal aquifer (being exploited since the beginning of the 1990s) – a subject of this paper – occurs within the Middle Triassic limestone-dolomites and in the overlying Middle Eocene Nummulitic limestones and carbonate conglomerates. These formations are found over the entire Podhale system, prolonging to the Slovakian territory. Usually their total thickness is considerable ranging from 100 to 700 m, while the effective thickness is equal to 100 m. The water circulation and high flowrates are primarily conditioned by the secondary fractured porosity and permeability. The Triassic reservoir rocks are fractured and brecciated due to the long tectonic transportation, vertical movements, weathering, karstification, and secondary dolomitisation processes. Moreover, these features make the carbonaceous rocks supple to the inflow stimulation treatments by acidizing. In such conditions, the flowrate from individual wells increases several times, occasionally even 20 times. On the contrary, the Middle Eocene rocks which were deposited *in situ* and did not undergo such a complex tectonic evolution, are generally characterised by weaker reservoir parameters and lower liability to the inflow stimulation. However, at the outcrops along the Tatra Mts. they form a good collector of drinking water due to the karst processes, weathering and near surface relaxation.

### 4.3 Caprock

The caprock of geothermal aquifers is formed by the thick (up to 2.5-3.2 km) Palaeogene flysch formation characterised by very good insulation properties. It consists of shales, mudstones, and sandstones. The presence of geothermal aquifers and heat convection manifests within the flysch as a distinct thermal blanket effect recorded by the temperature logs (Figure 4.4). Due to the heating up, the caprock temperature is up to 10°C higher than that resulting from the geothermal gradient only.

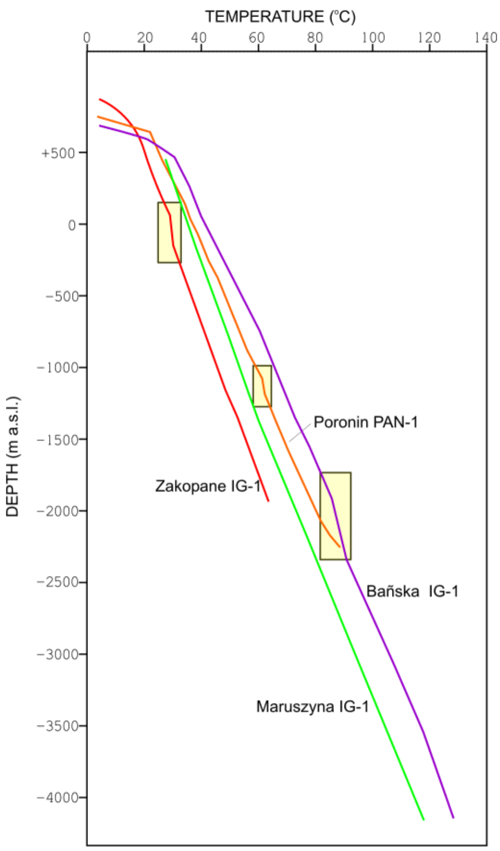


FIGURE 4.4: Temperature logs from some wells drilled within the Podhale region. Marked is a blanket effect in caprock of main geothermal aquifer (Kepinska, 2000)

## 4.4 Tectonics

The discussed system has a complex tectonic structure. Beside the mentioned nappes and overthrusts, there exists a network of deep faults of regional range (some of them continue tens to hundreds of kilometres, reaching out far beyond the Podhale area). Consequently, the Mesozoic units have a block structure (more weakly evidenced in the Palaeogene flysch more liable to the discontinuous deformations). The faults and fractures control the water and heat circulation and their upflow from the deeper parts of the system. The spatial orientation of dislocations locally modifies the directions of water flow. The fault thrusts reach 200-500 m or even more. The presence of these displacements and discontinuities needs to be taken into account for proper field development and siting of geothermal wells, directional ones in particular. The further detailed recognition of the deep structure of the Podhale system can be possible thanks to applying advanced methods, e.g. the 3D seismic profiling. Recently, due to detailed exploration of the top of the geothermal aquifer for proper siting of future exploitation wells, some work has already been done.

It is interesting to mention that the dislocation zones also currently manifest some tectonic activity (at 30-40 year intervals). The last movements were recorded in 1996, and with the magnitude of ca. 4.5 on the Richter-scale, they were the strongest among those observed thus far.

## 4.5 Thermal features

The terrestrial heat flow amounts to 55-60 mW/m$^2$ (Plewa, 1994). The average geothermal gradient varies between 1.9 and 2.3°C/100 m. In some parts of the main aquifer, positive thermal anomalies were detected: the temperature at depth of 2-3 km amounts to 80-100°C (Figure 4.3); i.e. higher than that resulting from the geothermal gradient. Apart from heat convection within the aquifer, this effect can be explained by increased upflow of heat and/or hotter fluids from the deeper part of the system along the planes of discontinuities (Kepinska, 1994). In particular, it refers to the northern part of the system bordering with the Pieniny Klippen Belt – former subduction zone. The role of this zone in creating thermal conditions of the Podhale system is certainly very important, but so far, insufficiently understood. The up-to-date results of geophysical exploration have shown that the zero induction anomaly is ascribed to it. This suggests the occurrence of geothermal fluids at great depth (6-16 km) and increased upflow of heat and hot fluids (Jankowski et al., 1982), as well as their inflow into the geothermal aquifers. This supposition has been supported by the surface thermal anomalies on the tectonic contact of the Podhale Basin and the Pieniny Klippen Belt recorded by 2-3°C higher than the average background values (Pomianowski, 1988; Figure 4.5). Besides, other surface research on the zones of regional dislocation within Podhale have shown them being privileged paths of increased heat transfer (Kepinska, 1997; Kepinska, 2000). Since some of them are still tectonically active, they can play an important role in the discussed heat transfer, too.

The Podhale geothermal system and the neighbouring systems in Slovakia (i.e. the Skorusina and the Poprad systems, respectively to the west and east of it, and the Liptov system to the south of the Tatra

Mts. recharge area) are similar in thermal properties. They all occur within the Inner-Carpathian Palaeogene, where numerous thermal anomalies produced by convective heat transfer in water-bearing formations are recorded. Higher values of the heat flow and geothermal gradient, as well as the increased thermal activity, appear in the most southern area of the Inner Carpathians. Neogene volcanic rocks are present (Koszyce region and Panonian Basin). The heat flow may reach a value from 80 to 100 mW/m$^2$ there. That greater geothermal effect is produced by the Neogene volcanism, while the increased heat upflow from the upper mantle of the Earth is of minor importance.

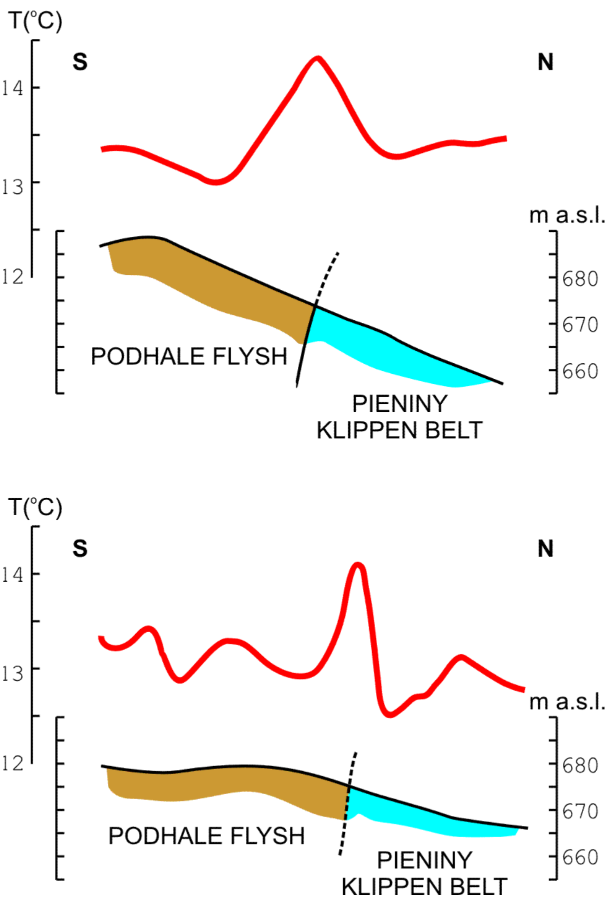

FIGURE 4.5: Surface thermal anomalies above the tectonic contact zone between the Podhale geothermal system and the Pieniny Klippen (according to Pomianowski,1988)

## 4.6 Hydrogeology

### 4.6.1 Conditions of water recharge and circulation

The main recharge area of geothermal aquifers is situated in the Tatra Mts. Generally, the water flows in the NW and NE-directions, and such a distribution is conditioned by the impermeable northern barrier of the Pieniny Klippen Belt (locally the directions of water flows are modified by the system of faults and fractures). The structure of the basin makes the system have artesian conditions (Figure 4.3). This is a valuable advantage of the reservoir - during exploitation, energy consumption for pumps can be limited.

The present artesian conditions of geothermal aquifers started to form at the turn of the Palaeogene (Oligocene) and Neogene when the Tatra massif and Pieniny Klippen Belt were uplifting, simultaneously with the lowering of the Podhale Basin. With the progressing erosion and denudation of the Palaeogene flysch covering the Tatra Mts., the Nummulitic Eocene, Mesozoic and crystalline series cropped out; so far they have functioned as an area recharging geothermal aquifers with meteoric waters. Prior to the above-described process, other hydrogeological and thermal conditions existed.

The flowrate of groundwater and consequent intensity of its exchange, decrease to the north up to the Klippen Belt border. Presumably, the flowrate in the southern part of the system amounts to several tens of metres/year while in the north close to the Pieniny it reduces to only a few metres/year.

It is worth noting that the Tatra Mts. act as a recharge area for geothermal aquifers occurring both to the north (the Podhale system) and to the south (the Slovakian systems). However, there are some differences in the chemistry of geothermal waters in the north and south due to the asymmetric lithological structure of the Tatras. The southern area of the Tatra Mts. recharging the Slovakian aquifers is almost entirely built of granitoids and metamorphic formations while the northern area recharging the Podhale system is built of sedimentary cover (limestones, dolomites, sandstones, clays).

### 4.6.2 Origin, age and chemistry of geothermal waters

The Podhale geothermal waters are predominantly of meteoric origin. Geologically, they are young waters, the age of which is from 10 years to 10-20 thousand years (Quaternary, Holocene). The TDS is low, in the range of 0.1-3 g/l. The water type is Ca-Mg-$SO_4$-Cl or Ca-Mg-$HCO_3$, with a small admixture of $H_2S$. The low TDS values and chemical water composition are of great advantage because of already observed and predicted moderate scaling and corrosion during exploitation.

Throughout the geological history, waters of different origin, age and chemical composition appeared within the Podhale system. Older waters (marine or meteoric) were gradually replaced by younger ones (Kepinska, 2000).

The water composition reveals the features typical of the washing of the formations saturated with saline water in the most recent geological time. Values of the hydro-geochemical ratio rNa/rCl based on the ion exchange suggest the final stage of sweetening of the exploited water (Figure 4.6). Moreover, it seems to prove that laminar water flow does not influence the elevated salinity (Kepinska, 2001).

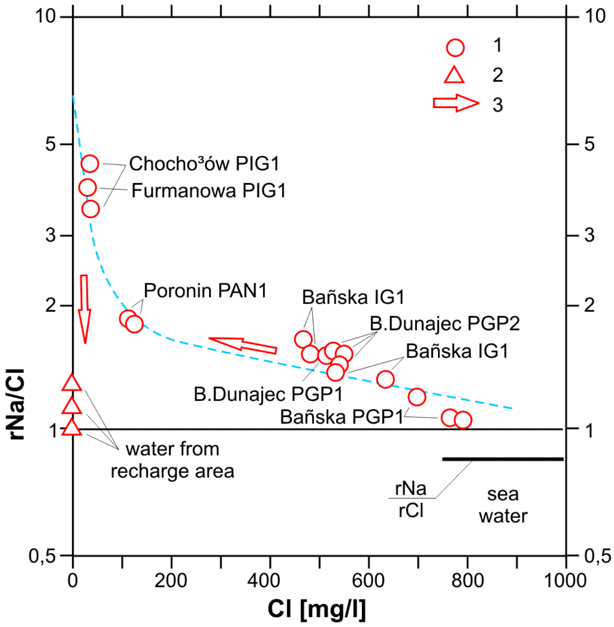


FIGURE 4.6: Change in rNa/rCl factor as assumed result of decreasing the mineralization of water from the main geothermal aquifer by meteoric water (Kepinska, 2001)
1. geothermal wells; 2. average values for the Tatra Mts. massif water; 3. direction of water mineralization decrease

### 4.6.3 Main reservoir and exploitation parameters

In the main geothermal aquifer, the artesian flowrate from individual wells varies from several to 550 $m^3/h$. If the inflow-stimulation treatment acidizing of carbonate reservoir rocks is performed, the flowrate increases markedly from 10-20s $m^3/h$ to over 20 times: up to 90-270 $m^3/h$ and even up to 550 $m^3/h$ (in terms of artesian outflow). The latter is among the highest values obtained in terms of self-outflow in Europe!

The main importance to high production from the wells is the secondary fracture porosity of 10-20% and intrinsic permeability up to 1000 mD supported by the presence of fractures and voids of karst origin. In contrary, the values of primary porosity and intrinsic permeability reach up to 3-4% and 0.01-1 mD, respectively.

Taking into account its inhomogeneity, the permeability of the main geothermal aquifer may be accepted to be on the order of $10^{-3}$ $m^2/s$. As previously mentioned the thickness of the main reservoir rocks is considerable (although variable) and equals 100-700 m, while the effective thickness amounts to 100 m. The greatest thickness was found in the northern exploited sector of the system.

The wellhead static pressure amounts to 26-27 bar. The reservoir temperatures within the deepest parts of the main aquifer (depths of 2-3.2 km) are as high as 80-100°C, while the wellhead temperatures reach up to 86-93°C. Within the deeper parts of the system, the measured formation temperature reaches 120-130°C (depths of 4.5-4.8 km).

### 4.7 Hydrothermal mineralogy

The present and past geothermal conditions of the Podhale system have been recorded in hydrothermal effects and mineral alterations. However, some hydrothermal minerals found in the Mesozoic rocks had been formed prior to Tertiary, i.e. before the Podhale geothermal system started to originate. Hydrothermal genesis can be ascribed to the part of minerals filling some generations of veins (e.g. calcite, dolomite, quartz). Interesting ore mineralisation also has the same type of origin (pyrite and other sulfates; Chowaniec et al., 1999). Part of the clay minerals were hydrothermally altered. The secondary dolomitisation of the Triassic limestones – the main reservoir rocks, is partly connected with the hydrothermal processes, too. The rock corrosion, especially washing of the veins and fractures with geothermal waters, is also observed (see also Appendix 1).

### 4.8 Surface manifestations

The system produces distinct (although rare due to the thick caprock) surface manifestations. In the zone of the tectonic contact of the Tatra Mts. and the Podhale Basin, a 20°C warm spring was flowing until the 1960s (then disappeared as a result of mixing with shallow cold water). It was already described scientifically in the middle of the 19th century. There are known travertine precipitations formed above the zones of deep regional faults, single evidences of thermal palaeokarst, and positive thermal anomalies (previously mentioned). The surface manifestations such as warm springs, travertines, and hydrothermal alterations are more abundant within the Slovakian side of the system (both on its north and south side).

## 5. HISTORY OF GEOTHERMAL RECOGNITION AND ITS USE

A warm spring in a suburb of Zakopane has been known at least since the $19^{th}$ century. The water of approx. 20°C was used in a swimming pool, particularly popular at the beginning of the $20^{th}$ century. In the 1950s, the spring disappeared due to the mixing with cold river water. The spring was an important premise of geothermal occurrence in the Podhale. Just before 1939, it induced a rising of geothermal theories and the first well design recognising the site. However, the first well in the Podhale was not drilled untill in the years 1961-1963.

In 1963, the first deep exploration well, Zakopane IG-1 (3073 m) was drilled (Sokolowski, 1973). It recognised several geothermal aquifers. The main ones belong to the Eocene carbonates and Jurassic marls and marly limestones. The latter are most productive (1540–1620 m) and were put into exploitation. Their main parameters were as follows: artesian outflow 50 $m^3$/h (14 l/s), wellhead temperature 36°C, TDS 0.3 g/l. In 1973, the second well, Zakopane-2, was drilled there. High artesian water flowrate, 80 $m^3$/h (22 l/s), from the Eocene limestones (at a depth of 990-1113 m) was obtained, while the wellhead temperature was 26.6°C and the TDS about 0.3 g/l (Malecka, 1981). Until 2001, waters at temperatures of 26°C and 36°C, produced by these two wells were used for two bathing pools. Since mid-2001, the construction of a large geothermal balneo-therapeutical and recreational centre has been underway there.

Between the 1970’s and 1980’s, several wells were drilled along the southern boundary of the Podhale system, close to the Tatra Mts. They were oriented mostly for geological exploration and potable water intake. In some cases, artesian outflows of geothermal water up to 20ºC were obtained.

From 1979-1981, a breakthrough was made in the development of geothermal energy use for heating purposes, when the Banska IG-1 well (total depth 5263 m) was drilled. It confirmed the existence of rich geothermal aquifers with advantageous reservoir parameters within the entire Podhale basin. The main aquifer was found in the Middle Triassic limestones – dolomites and in underlying Eocene carbonates. It is situated directly beneath the Palaeogene Flysch formation, and its main parameters were as follows: water outflow (artesian) - 60 $m^3/h$ wellhead temperature 72°C, TDS 3 g/l, wellhead static pressure 27 bars (Sokolowski, 1993).

The geothermal water revealing such parameters proved useful for local space-heating. It brought up the possibility to replace the ineffective and polluting coal-based heating system. The argument was solid enough to develop geothermal heating in the Podhale to protect the environment and preserve its unique value.

The preliminary estimation of the geothermal potential was carried out. The obtained results induced the intense exploration activities aimed at wide geothermal development. In particular, a detailed investigation project to evaluate the geothermal reserves of the Podhale Basin was carried out from 1987-1995. Several scientific institutions participated in the project, namely: the State Geological Institute, the University of Mining and Metallurgy in Krakow, Polish Oil and Gas Company and Mineral and Energy Economy Research Institute (former Centre) of the Polish Academy of Sciences.

The project comprised desk studies of the numerous past surface and underground investigations from the point of view of the geothermal prospects and new works including first of all drilling five deep wells (2394-3572 m) in the central and northern part of the Podhale basin over the years 1988-1992. Logging and well tests confirmed the occurrence of the geothermal reservoirs within the Podhale Basin. They provided new more detailed data testifying very favourable reservoir properties of the main geothermal aquifer in the Middle Triassic and Eocene carbonates. It gave a solid basis and minimised the risk of further works for the introduction of the geothermal space-heating in the Podhale region.

From 1989-1994, the first experimental geothermal plant was designed, constructed, and put into operation in Poland by the team from the PAS MEERI. During the 1993/94 heating season, the first six buildings in the village of Banska Nizna started to be supplied with geothermal heat from the plant (Sokolowski et al., 1992). It was a milestone of the activities oriented toward geothermal space-heating, both in Podhale and Poland.

In 1994, upon completion of the pilot stage, to conduct all the work concerning the construction of the regional geothermal heating network, the joint stock company called Geotermia Podhalańska S.A. was founded. The shareholders were the Podhale region communities, the Polish Academy of Sciences, the National Fund for Environmental Protection and Water Management, Hydrotrest S.A., and other smaller ones. In June 1998, a new company – the "Geotermia Podhalanska S.A. District Heating Company" took over project development. In 1995, the Geothermal Laboratory of the PAS MEERI superseded the experimental geothermal plant to continue further research and implementation works.

Since 1994/1995, the geothermal works in the Podhale region have been carried out on two basic paths:

- Construction of the regional geothermal space-heating system – by PEC Geotermia Podhalańska S.A. (more in Section 7);
- Basic research, and R&D works on cascaded uses, education and promotion - by the PAS MEERI Geothermal Laboratory (more in Section 8).

## 6. GEOTHERMAL WATER EXPLOITATION AND HEAT EXTRACTION – METHOD STATEMENT

From its beginning, the Podhale project assumed a close-working system of geothermal reservoir exploitation, heat extraction, and distribution to the receivers. It was planned to extract the heat from geothermal water through heat exchangers while cooled geothermal water was injected back to the same reservoir. Such a method would assure long-term sustainable water and heat production from the field.

Since the end of 2001, geothermal water has been produced by two wells: Banska PGP-1 and Banska IG-1. The maximum self-outflow from the PGP-1 well amounts to 550 $m^3$/h of 87ºC water. The TDS are relatively low, ca. 2.5 g/l, while the static artesian pressure is equal to 27 bar. The maximum self-outflow from IG-1 well amounts to 120 $m^3$/h of 82ºC water. The TDS are ca. 2.6 g/l, while the static artesian pressure - 26 bar. In the exploited sector of the Podhale system, the geothermal aquifer is situated at a depth ranging from 2048-2113 m (top) to 2394-3340 m (bottom). The effective aquifer thickness was estimated for 100 m, while in total it reaches about 700 m. Geothermal water is transported to the plate heat exchangers in the Base Load Plant. In 2003, its installed capacity was 38 $MW_t$ (planned ca. 60 $MW_t$). Heated to 70-83ºC, the network water is supplied through transmission and distribution pipelines to the consumers who have individual node heat exchangers to consume heat from the main pipeline. Cooled geothermal water of a current temperature drop not exceeding 25-30ºC is sent through a pipeline to the pumping station. Then it is injected back to the reservoir through two injection wells: Bialy Dunajec PAN-1 and Bialy Dunajec PGP-2 (the maximum injection pressure is 55-60 bar). The maximum amounts of water to be injected through the Bialy Dunajec PGP-2 well and the Bialy Dunajec PAN-1 well are 400 $m^3$/h and 200 $m^3$/h, respectively. The distance between production and injection wells is 1.2-1.7 km. Main data on geothermal wells are summarised in Table 4.1.

TABLE 4.1: The Podhale region – main data on geothermal wells exploited for space-heating

| Well | Banska IG-1 | Banska PGP-1 | Bialy Dunajec PAN-1 | Bialy Dunajec PGP-2 |
|---|---|---|---|---|
| Year of drilling | 1979-1981 | 1997 | 1989 | 1996-1997 |
| Year of starting | 1992 | 2001 | 1992 | 2001 |
| Role in the system | Production | Production | Injection | Injection |
| Total depth (m) | 5261 | 3242 | 2394 | 2450 |
| Reservoir depth (m) | 2565-3345 | | 2113-2394 | 2048-2450 |
| Lithology | Carbonate conglomerates, limestones, dolomites (Middle Eocene-MiddleTriassic) | Carbonate conglomerates, limestones, dolomites (Middle Eocene-MiddleTriassic) | Carbonate conglomerates, limestones, dolomites (Middle Eocene-MiddleTriassic) | Carbonate conglomerates, limestones, dolomites (Middle Eocene-MiddleTriassic) |
| Production casing | Casing 6 5/8", perforated interval 2588-2683 m | Casing 6 7x75/8", perforated interval 2772-3032 m, open hole 3032-3242 m | Casing 9 5/8", perforated interval 2117-22132 m, open hole 2132-2394 m | Casing 9 5/8", perforated interval 2040-2450 m |
| Maximum production ($m^3$/h) | 120 | 550 | | |
| Maximum wellhead temperature (°C) | 82 | 87 | | |
| Static wellhead pressure (bar) | 26 | 27 | 55-60 | 55-60 |
| TDS (g/$dm^3$) | 2.5 | 2.7 | | |
| Maximum injection capacity ($m^3$/h) | | | 200 | 400 |

During 1992-2001, i.e. in the pilot stage of the Podhale project, and at the beginning of its main stage, the exploitation and heat extraction system operated on one well doublet: Banska IG-1 (production) and Bialy Dunajec PAN-1 (injection). The production amounted to 30–60 $m^3$/h of 76–80°C water. The geothermal heat was transmitted to the district heating through two heat exchangers. Their installed capacity was 4 $MW_t$, the real one during the heating season was up to 2 $MW_t$. After heat extraction, the geothermal water was injected back to the same reservoir by the Biały Dunajec PAN-1 well.

This doublet served the heating network in almost 200 individual dwellings (about 1000 inhabitants), a school, church, and cascaded use installations. Maximum geothermal heat production was ca. 30 TJ/y for space-heating in Banska Nizna village. The sketch of a geothermal doublet working from 1992 to 2001 is given on Figure 4.7. In October 2001, the existing network was joined in the extended exploitation system that was put into operation thanks to two new wells: Banska PGP-1 (production), and Biały Dunajec PGP-2 (injection). The wells were drilled during 1997-1998, and their owner is the PEC Geotermia Podhalańska S.A.

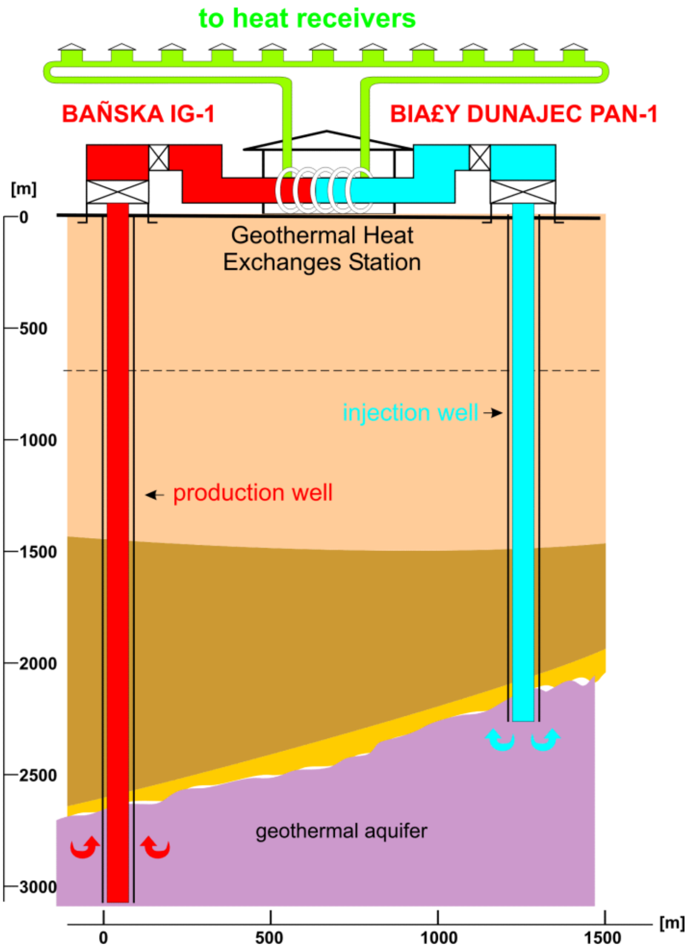


FIGURE 4.7: Sketch of the geothermal doublet working from 1992-2001, PAS MEERI Geothermal Laboratory

## 7. THE PODHALE GEOTHERMAL HEATING PROJECT

### 7.1 Main objectives

As mentioned before, the project to construct a geothermal space-heating network within the Podhale region was initiated by the Polish Academy of Sciences, Mineral and Energy Economy Research Centre (Ney and Sokolowski, 1987). In the period 1989–1993, the experimental geothermal plant was built. In late 1993, the first six houses in the village of Banska Nizna were connected to the plant. This was the pilot phase of the utilisation of the geothermal heat in the Podhale region and in Poland, in general (Sokolowski et al., 1992). Since 1994, after the pilot stage had succeeded, PEC Geotermia Podhalańska S.A. conducted the full scope of activities related to construction of the regional geothermal heating network within the Podhale region.

The main objective of the project is to reduce air pollution and to improve the state of the natural environment. It is of fundamental importance to the further development of this region in Poland, because of its natural values and tourist character. The project assumes that geothermal energy will replace the consumption of fossil fuels – in particular coal – for space- heating and domestic warm-water. Due to some years' project experience and ongoing optimization of the initial assumption, it is expected that about 2000 residential and commercial buildings will be connected to the geothermal heating system.

### 7.2 Background

The Podhale region may be divided into three areas occupied by the valleys of the three main rivers, flowing from the Tatra Mountains towards the north (Figure 4.2). These valleys can be considered as three natural, separate district heating systems: west, central and east. The biggest is the Central Valley, i.e. the Biały Dunajec River Valley system – the most densely populated area, where the two main cities of this region, Zakopane and Nowy Targ, are located. Two others are the West Valley - Czarny Dunajec River, and the East Valley - Białka River systems.

In 1993, scientists from the PAS Mineral and Energy Economy Research Centre, and experts from House & Olsen Thisted Ltd., Denmark elaborated the feasibility study for geothermal heating in the Podhale region. It was assumed that 60–70% of consumers in small villages would be connected to the network, while 70–80% in larger villages, and 100% in towns (Sokolowski, 1993). The above percentage was successively corrected in the course of the project realisation according to the current circumstances. The state of reservoir exploration, the number of existing wells, and the most dense population were the reasons for the first steps towards geothermal heating to be taken just in the Central Valley - in Banska Nizna village in 1993 when the experimental geothermal plant was launched. The next step started to be developed in the town of Zakopane, where the heat consumption is the greatest. The second main town of the region, Nowy Targ, is expecting to be partly connected to the geothermal network in 2004-2005.

Initially, the installed thermal power for the Central Valley System – a priority of the project - has been estimated at 150 $MW_t$ (including about 78 $MW_t$ from gas peak boilers). In the 1994-2003 period, further detailed studies and optimisation work were carried out. On the basis of the recent results of 2003, it was assumed that the thermal capacity of the geothermal system in this valley will amount to 80 $MW_t$ and the heat output will reach a level of 600 TJ/year. It will be achieved due to connecting about 2,000 receivers to the geothermal network by the end of 2005 (Dlugosz, 2003). The anticipated heat sales upon project completion for different consumers categories is given in Table 4.2.

TABLE 4.2: The Podhale geothermal project – specification of geothermal heat consumers and calculated heat demand (Dlugosz, 2003)

| Category – number of users | Calculated annual heat consumption (TJ/a) | Percentage of total consumption (%) |
|---|---|---|
| Households – 1500 | 150 | 25 |
| Large and medium consumers – 260 | 320 | 53 |
| Nowy Targ – sale for municipal heating plant | 130 | 22 |
| TOTAL | 600 | 100 |

The technical diagram of the geothermal heating system under construction in the Podhale region is shown in Figure 4.8.

## 7.3 Energy sources

The heating system is planned to be based on three energy sources. Currently (2003), two of them are in use (location: Figures 4.3 and 4.8):

- Geothermal base load plant in Banska Nizna;
- Gas and oil peak load plant in Zakopane.

After connecting the buildings in Nowy Targ, a gas or oil plant in that town will work as a peak load, and a third heat source in the system. The role of the above sources in the constructed system can be briefly characterised as follows:

**Geothermal base load plant, Banska Nizna.** The total geothermal capacity of installed plate heat exchangers can reach 60 $MW_t$ (38 $MW_t$ in 2003). The plant is based on two production wells PGP-1 and IG-1, capable to totally discharge 670 $m^3/h$ of 82-87ºC water (Table 4.1). Geothermal heat is transmitted to the district heating water through plate heat exchangers (7 $MW_t$ each, 40°C maximum

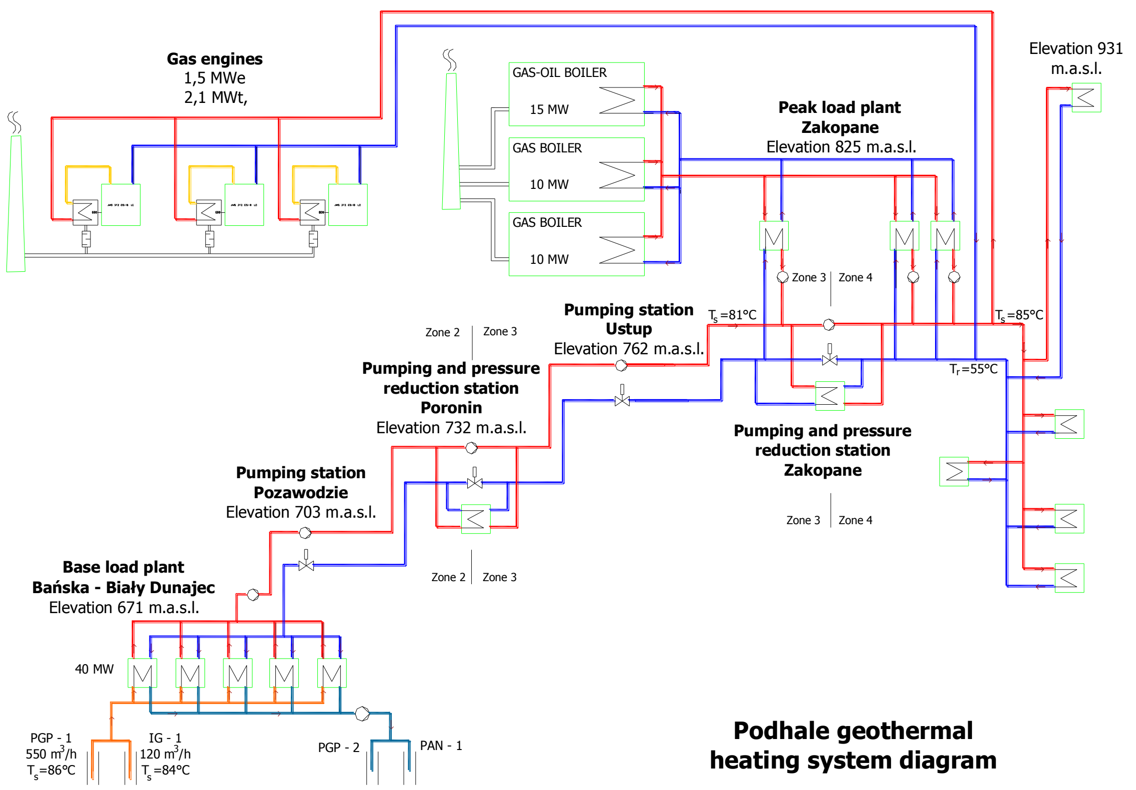


FIGURE 4.8: Technical diagram of the geothermal heating system under construction in the Podhale region (Dlugosz, 2003)

cooling of geothermal water, current up to 25-30°C). After passing heat exchangers, the cooled geothermal water is injected back (via pumping station) to the reservoir through two injection wells situated 1.2-1.7 km from the production wells. In the plant, other technological facilities are installed. They are the circulation water treatment system with a capacity of ca. 50 $m^3$/h, the expansion system protecting particular pressure zones, and the circulation pumps with a capacity of 3x470 $m^3$/h, pumping water towards Zakopane, and 3x150 $m^3$/h towards Nowy Targ (planned).

**Central peak load plant, Zakopane.** Its target capacity ca. 44 $MW_t$ was reached in 1998-2001, i.e. until the geothermal heat had been delivered to Zakopane, the main town of the region, via the main transmission pipeline from Banska, the plant was working as a basic gas heat source.

Since 2001, i.e. after connecting the heating system in Zakopane to the Base load plant, the plant has two basic functions:

- Peak heat source;
- Reserve heat source (for consumers located between the Poronin pressure separation station and Zakopane).

In 2003, the Central peak load plant was equipped with three gas and gas-oil boilers (total 35 $MW_t$ capacity), with economizers (1 $MW_t$ capacity each) to recover the condensation heat contained in the outlet combustion gases, and three co-generation gas engines (1.5 $MW_e$ and 2 $MW_t$). The boiler system is hydraulically separated from the network by three plate heat exchangers (each of 17 $MW_t$ capacity) (Figure 4.8).

### 7.4 History and 2003 year's state of the project

The construction of a geothermal heating network in the Podhale region (Bialy Dunajec River Valley) was planned to be carried out in stages during 1989–2002, but the real date of completion is expected in 2005. The beginning stage (1989–1995*)* comprised the construction of the experimental geothermal plant and the connection to the first consumers. It was followed by the construction of the district-heating network supplying about 195 buildings in the village of Banska Nizna. This stage served as a control, testing the validity of the assumption and operation efficiency of the system.

The main items of the Podhale geothermal project realised in 1995-2003 can be summarised as follows:

- Drilling of two wells: Banska PGP-1 (production) and Biały Dunajec PGP-2 (injection);
- Well tests and inflow-stimulation treatments in five geothermal wells previously drilled;
- Construction of the Geothermal base load plant in Banska Nizna;
- Construction of the Peak load plant in Zakopane;
- Construction of the Banska – Zakopane DN 500 main transmission network, total length of 14 km. The network transmits geothermal energy from the Geothermal base load plant to the Central peak load plant in Zakopane through several villages;
- Growth of the distribution networks in Zakopane and some villages located between the base load and Zakopane;
- Conversion of individual and large heat consumers in Zakopane and other localities;
- Rebuilding of the heating and distribution networks in Zakopane and several villages;
- Conversion of coal and coke boiler houses on heat exchanger units;
- 3D-seismic survey for selected sectors of the Podhale system aimed at properly siting new exploitation wells and getting detailed knowledge on tectonic structure of geothermal aquifers and flow directions.

The works to be completed by 2005 include drilling of a geothermal well for the heating needs of the Nowy Targ area (possibly), construction of the main pipeline to Nowy Targ, construction of the distribution network in the villages situated on the way to Nowy Targ, rebuilding of the Geothermal base load plant in Banska Nizna due to the needs of Nowy Targ, and construction of a ca. 25 $MW_t$ Peak load plant in Nowy Targ.

In the future, PEC Geotermia Podhalańska S.A. will develop the market for low-parameter energy based on the return water of the heating system and cooled geothermal water sent to the injection wells. An individual tariff system will be established, making it possible to develop investments in such sectors as greenhousing, swimming pools, recreation centres, floor heating systems, etc.

Some photographs of the main facilities of the Podhale geothermal space-heating network are shown on Figures 4.9 - 4.12.

FIGURE 4.9: Geothermal base load plant, Banska Nizna – general view (photo T. Kliszcz)

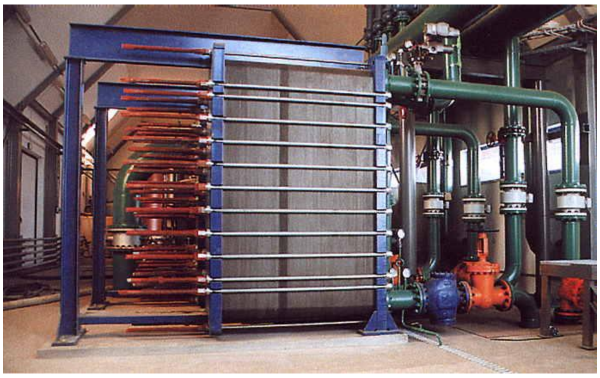

FIGURE 4.10: Geothermal base load plant, Banska Nizna – plate heat exchangers (photo T. Kliszcz)

FIGURE 4.11: Central peak load plant, Zakopane – general view (photo T. Kliszcz)

## 7.5 Heating networks

FIGURE 4.12: Central peak load plant, Zakopane – inside view (photo T. Kliszcz)

Prior to the geothermal project, only part of the town of Zakopane was provided with a heating network. Therefore, most of dwellings both in Zakopane and Podhale's villages were heated by their individual heat source. Due to the great area of the developed project, the construction of the heating networks involved a major amount of expenditures (Dlugosz, 2003). A 90/50°C heating network between energy sources and consumers has been built practically from scratch. The main pipeline towards the town of Zakopane is built of preinsulated pipes with small heat losses. The temperature drop is not higher than 2°C over a distance of 14 km. Because the temperature of network water after passage through heat exchangers is 82-83°C, that gives a temperature of ca. 80°C for the feed to the major customers in Zakopane. In summer, to ensure warm domestic water, the temperature of the supply will be not lower than 60-65°C. All pipelines of DN 100 and more in diameter are equipped with leakage detection system. Generally, the system consists of three circulation loops:

- Geothermal circulation, with a standard pressure of 40 bar in the Base load plant and 64 bar behind injection geothermal pumps;
- Network water circulation with a standard pressure of 16 bar;
- Boiler circulation in Peak load plants with a standard pressure of 6 bar.

To compensate for the large differences in ground topography and to avoid pressure from exceeding 16 bar, the network water system was divided into four pressure zones (Figure 4.8).

## 7.6 Heat consumers

The geothermal heat consumers have been divided into two main groups depending on the thermal power demand:

- Individual households with capacities from several to a dozen kilowatts. They are equipped with compact heat exchangers. They are dual-function plate heat exchangers (warm-water production for the central heating and domestic water, in a flow system without a hot-water bunker);

- Medium consumers (boarding houses, offices, schools, public buildings, etc.) and large consumers (buildings heated formerly by small, local coal-based boilers). They are equipped with compact dual-function plate heat exchangers, and additionally with an automatic weather-sensitive system, with the possibility of programming many functions such as night drop, wind impact, etc.

All heat exchangers are equipped with heat meters.

### 7.7 Outlays of investment and sources of financing

The outlay for the project, of the greatest range of investment, was planned for about 90 million USD. It presumed the greatest geographical range, and the greatest sale of heat, which would result in the greatest positive impact on environmental protection by connecting to the network the greatest numbers of receivers. Due to project optimisation with time and of limiting its scope, the total costs were lower. The investment is financed from Polish and foreign sources including share capital, grants, loans, and credits (Table 4.3). They are as follows:

- Polish sources: the capital of the company PEC Geotermia Podhalańska S.A.; Ekofund; the National Fund of Environmental Protection and Water Management; Bank PKO;
- Foreign sources: PHARE EU; Large-Scale Infrastructure Projects EU; the Global Environment Facility (GEF); credits: the Bank of Environmental Protection; the Danish Environmental Protection Agency (DEPA); and the World Bank.

The capital expenditures over the period of 1994-2003 totalled about 212 million zl (about 53 million USD). It should be mentioned that a part of this comes from Ekofund. This fund was established on the basis of the Polish foreign dept extinguished for ecological purposes. The great benefit for the Podhale region is a high percentage of grants (near 50%) in the financing.

TABLE 4.3: The Podhale geothermal project – capital expenditures 1995-2002 (Dlugosz, 2003)

| Source of finance | Million Euro | (%) |
|---|---|---|
| Share capital | **9,900** | **18.8** |
| Grants | **26,175** | **49.7** |
| PHARE | 17,700 | |
| NFEPWM | 2,650 | |
| Ekofund | 1,050 | |
| GEF | 2,500 | |
| USAID | 1,750 | |
| DEPA | 525 | |
| Credits | **16,625** | **31.5** |
| World Bank | 10,525 | |
| Bank PKO | 6,100 | |
| **TOTAL** | **52,700** | **100.0** |

1 PLN = about 0.25 USD
PHARE – Poland Hungary Aid for Reconstruction;
NFEPWM – National Fund for Environmental Protection and Water Management;
GEF – Global Environmental Fund;
USAID – United States Agency for International Development;
DEPA – Danish Environmental Protection Agency

### 7.8 Ecological results

Ecological benefits were the main and the strongest arguments for introducing geothermal space-heating within the Podhale region. The realisation of the project will bring measurable results in the elimination of a considerable part of over 200,000 tonnes of coal and coke burnt per year in that region that will result in a decrease in related emissions.

By the end of 2002, 410 individual (small) consumers, 116 large-scale receivers and 25 local coal-fired space-heating plants that supplied over 100 blocks of flats have been connected to the geothermal network. Works on connecting new consumers are underway. Geothermal heat production in 2002 was 150 GJ (total 180 GJ). The project has been monitored as far as the limitation of emissions, such as CO, $SO_2$, and dust are concerned. In the case of Zakopane, thanks to the successive introduction of geothermal heating in this town in 1998-2002, annual average concentrations of particulate matter ($PM_{10}$) and $SO_2$ have dropped by about 50% in comparison to the situation before the geothermal heating was put on-line. Moreover, during the winter heating season of 2001/2002, the $SO_2$ concentration dropped by 67% as compared to the situation in 1994-1998 prior to geothermal heating initiation in Zakopane. Total $CO_2$ reduction in 2002 was 41,630 tonnes. Figure 4.13 shows the ecological effect expressed as limitation in $SO_2$ emissions generated so far mostly by coal-fired heating systems.

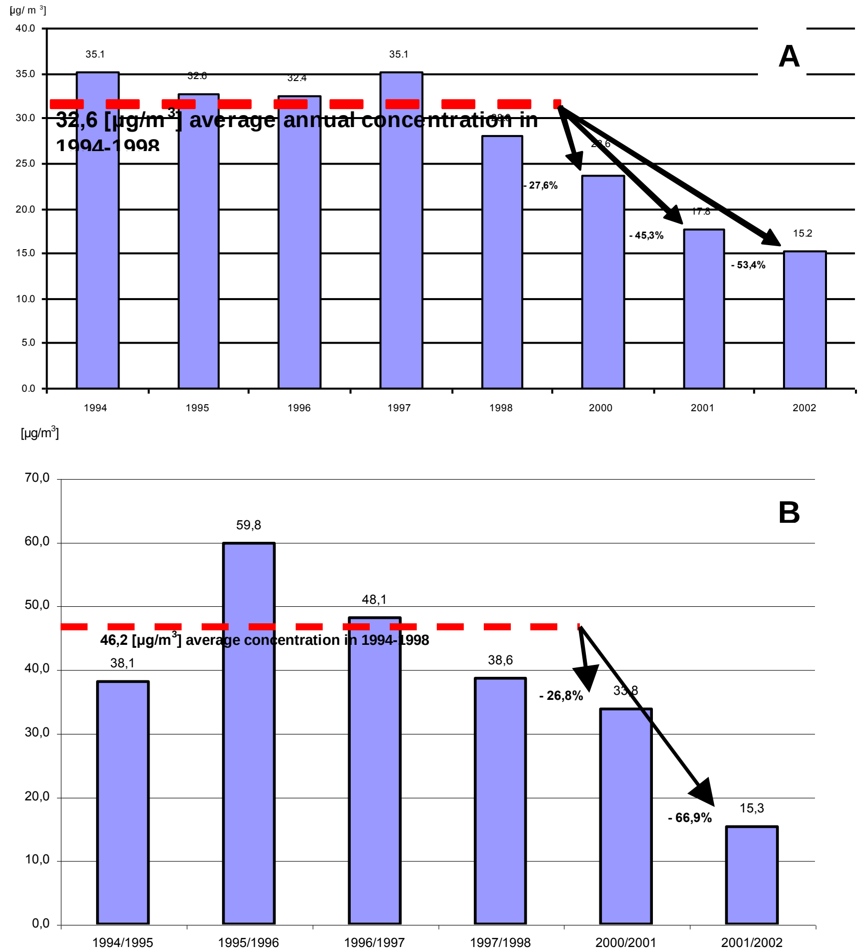


FIGURE 4.13: Limitation of main emissions resulting from the introduction of a geothermal space-heating system in Zakopane;
a) Average annual $SO_2$ concentrations;
b) Average $SO_2$ concentrations during heating seasons.
1994-1997 situation prior to geothermal project development when space-heating in the town was based on hard coal and other fossil fuels; 1998-2002 situation at the beginning of geothermal heating system in the town; 1998-2001 bulk of coal-based systems replaced by gas-fired Peak load plant; since 2001 development of geothermal space-heating system (data from Dlugosz (2003) and unpublished files, courtesy P. Dlugosz, PEC Geotermia Podhalanska SA.)

## 8. CASCADED GEOTHERMAL USES

Along with the geothermal space-heating project in the Podhale region, the PAS MEERI Geothermal Laboratory has conducted the R&D works on cascaded geothermal uses in a wide temperature range. It continues the scientific research, experimental and semi-technical work initiated by the experimental geothermal plant. Many of the projects – innovative in Poland – either have been completed or are underway thanks to the financial support from the State Committee for Scientific Research. The types of geothermal uses are those recommended both in the Podhale region and in other parts of Poland because of climatic conditions, types of agriculture, and market demand (Bujakowski, 2000b). The Laboratory conducts observation and monitoring of the geothermal reservoir and system under the conditions of long-term exploitation. This place serves also for demonstration and education purposes, being the only one of such a character in the country. The operating cascaded system is composed of the following (Figure 4.14):

- Space heating and domestic warm water supply to the buildings of the PAS MEERI Geothermal Laboratory;
- Wood-drying;
- Greenhouses;
- Stenothermal fish farming;
- Foil tunnels for growing vegetables in heated soil.

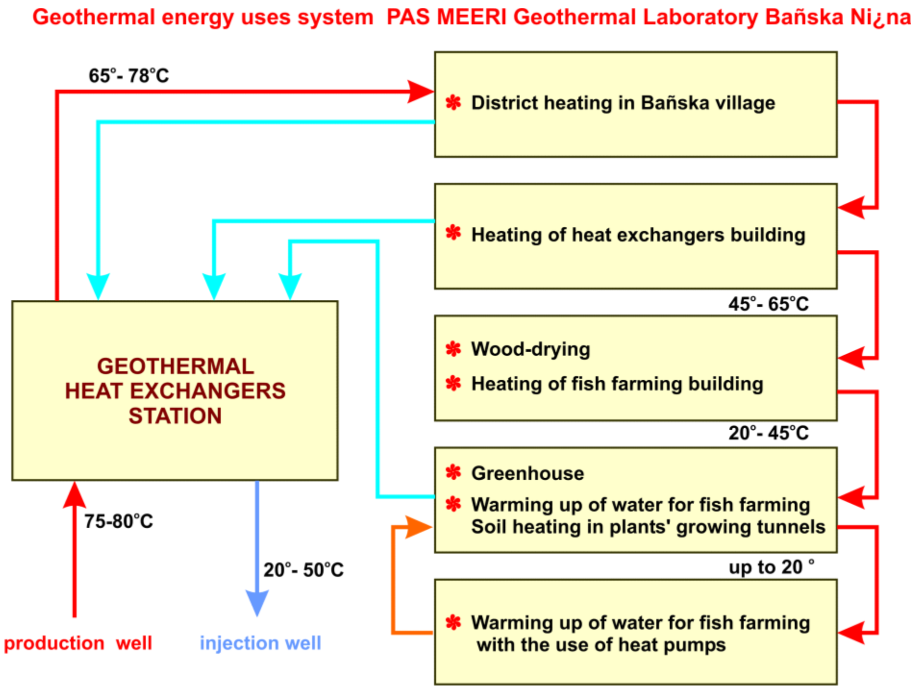


FIGURE 4.14: Sketch of cascaded uses system, PAS MEERI Geothermal Laboratory

The uses of special interest for the region and other parts of the country are:

**Wood-drying**. This is a typical wood-drying chamber, manufactured in serial production as a steel structure. It is heated by a Favier heater and its heat requirement depends on the degree to which the chamber is filled with wood for drying, fluctuating within the range of 21-120 kW. The inside temperature is 40°C, while the supplied heating water is 65/45°C. Depending on the humidity and the type of wood, the drying cycle usually takes 2-3 weeks. In natural conditions, 2-3 years on average are required for wood to acquire the parameters qualifying it for construction or other purposes. It is also proposed to use the clean geothermal heat for drying agriculture products.

**Stenothermal fish farming.** The building, 21.2 m x 12.25 m in dimension, was made using the energy-efficient Thermomur technology. Heat savings are considerable because the building uses approx. 60% of the energy needed for a traditional structure of the same size. The used technology is of particular significance because it ensures the required warmth (28-33°C) inside simultaneously protecting the building elements against condensation of the humidity coming from water evaporating from eight breeding tanks. The geothermal farming makes it possible to breed attractive stenothermal fish species such as African catfish or tilapia, and to achieve high weight-increase rates. The fish reach their commercial weight of 1-1.5 kg over a period of 6 months, while traditional breeding of two common fish species (carp and trout) in open cold tanks takes 2 years in the climate typical in Poland.

**Foil tunnels for growing vegetables in heated soil.** The foil tunnels have a heating installation in the soil. These are polyethylene pipes (DN = 32 mm and DN = 25.2 mm) laid at a depth of 30 cm under the soil surface at intervals of 25-30 cm. This solution resembles floor-heating systems used in buildings. The temperature of water in pipes amounts to 40-45º, heating the soil to 25-28ºC. When leaving the tunnels, the water temperature is 38-43°C. Due to the necessity of ensuring well-balanced distribution of temperatures in the top layer of the soil, the temperature drop along the heating pipe-layout is very small (approx. 2°C). Consequently, the heating capacity can be controlled solely by changing the flow of water through the pipes.

## 9. MONITORING AND PRODUCTION HISTORY OF THE PODHALE GEOTHERMAL SYSTEM

Since it was put into operation in 1990, when the exploitation through one doublet of wells Banska IG-1 - Bialy Dunajec PAN-1 started, the Podhale geothermal system has been the subject of monitoring. The visualisation and analysis of the main hydrodynamic, physical, and chemical parameters have been carried out. Both the PAS MEERI Geothermal Laboratory and PEC Geotermia Podhalanska S.A. commonly managing the production, carry out the observations. In the case of the latter company, the SCADA-system has been used both for geothermal and surface technical parts of the heating network.

From 1990 to 2001, during the exploitation of one doublet, water flowrate varied from 8-16 l/s while the wellhead temperature was 76-80°C. The maximum capacity reached 1.8 $MW_t$, and about 30 TJ/year were delivered to the space-heating network in Banska village. Until 2001, before two new wells started, the flowrate and temperature of water produced in the doublet Banska IG-1 – Bialy Dunajec PAN-1 was observed being stabilised. However, some slight pressure drop at the production well, and a pressure increase at the injection well were recorded. Among others, the reason for this may have been the slight decrease of permeability of the reservoir rocks, due to precipitation of secondary minerals and introduction of products of corrosion from the transmission pipeline into the reservoir. The monitoring showed also some decrease in TDS of the produced water – from 2.9 to 2.5 $g/dm^3$, while the water type did not change. In general, stability of the basic parameters of the exploited system was observed in the period 1990-2001. The recovery features of the reservoir were maintained. The results of the monitoring have proven the applied exploitation method to be correct, as it makes it possible to maintain the renewable features of the reservoir. So far, no drop tendencies have been observed regarding pressure, flowrate, and temperature of the produced water (Figure 4.15).

As already mentioned, in late 2001 the exploitation system was extended by two new wells Banska PGP-1 and Bialy Dunajec PGP-2. The amount of produced and injected water considerably increased, from a level of 30-60 $m^3/h$ to 100-500 $m^3/h$. Sustainable long-term field management requires recording the reservoir response for increased production, predicting its long-term behaviour, and keeping a stable level of the parameters.

The corrosive properties of geothermal water and its scaling tendency are also the subject of investigation since these effects are very significant to the reliability and uninterrupted operation of the system, as well as to the durability of both surface and downhole installations.

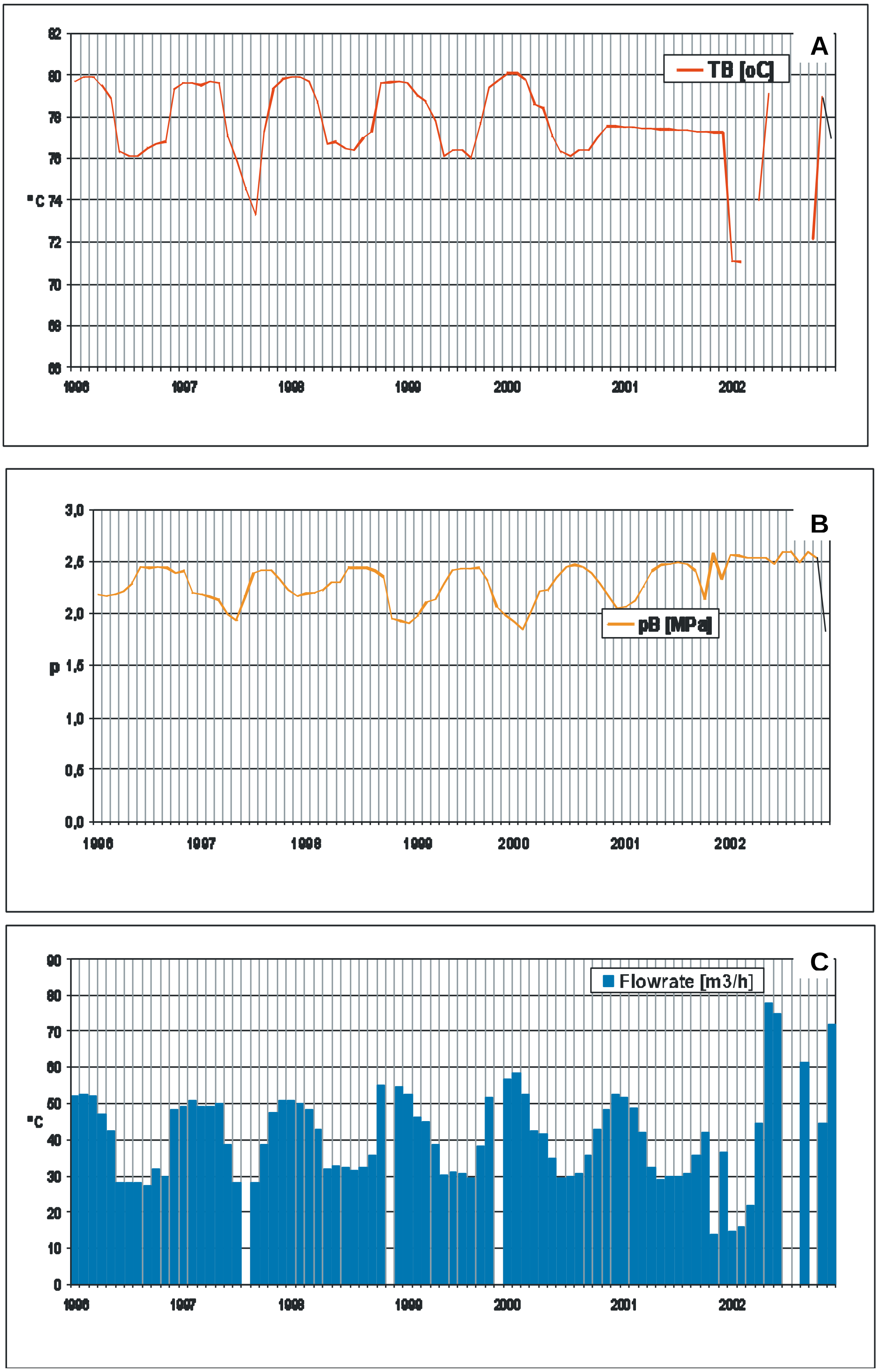


FIGURE 4.15: The Podhale geothermal system– production history of
Banska IG-1– Bialy Dunajec PAN-1 doublet of wells, 1995-2001
A. Temperature; B. Pressure; and C. Flow rate
(period of stable surface installations' conditions; in late 2001 the
exploitation was expanded by new production and injection wells)

## 10. SOCCIAL ASPECTS OF GEOTHERMAL ENERGY INTRODUCTION IN THE PODHALE REGION

The Podhale geothermal project has been accompanied by an information and education campaign. The authors of the project and contractors organised many meetings with residents of administrative localities being planned to join the geothermal heating network. Some local authorities support those efforts. The most important was to convince consumers about reliability of the geothermal source of heat, its competitive prices compared to traditional sources of heat, and ecological benefits rising the tourist value of the region. The project had to get social agreement for required technical changes and related costs. The pilot stage of the project had strong support from the community of the Banska Nizna. They established the Social Geothermal Committee, which assisted the contractor in the works concerning the village central heating. Common consumers of geothermal heat appreciate its benefits and advantages, mostly:

- Considerable comfort of operating the heating facilities;
- Greater possibility of regulation of temperature inside rooms;
- Possibility of observation of energy consumption, which may influence its saving;
- Limitation of air pollution in the close vicinity (particularly visible in winter);
- Geothermal heating in buildings attracts tourists for hire of rooms.

## 11. ECONOMIC ASPECTS OF GEOTHERMAL HEATING

For many people, the most important are the economic aspects of this type of heating. In the beginning, the price of heat negotiated by the Social Geothermal Committee in Banska Nizna, was reduced. Then the VAT value was also low – 7% against 22% at present. According to the announcement of the Energy Regulation Authority, the current price of geothermal heat is slightly higher than coal heat and lower than gas heat. If the labour costs are included, the price for geothermal is equal to coal (Figure 4.16). The cost of producing 1 GJ of heat at the Geothermal base load plant in Banska is around 10 PLN (2.5 USD). In the cost structure of producing 1 GJ of heat, the costs of electricity and natural gas amount to 25% only. A very high percentage of the expenses (10%) is connected with the new property tax (charged on built structures) introduced in 2002 (Dlugosz, 2003).

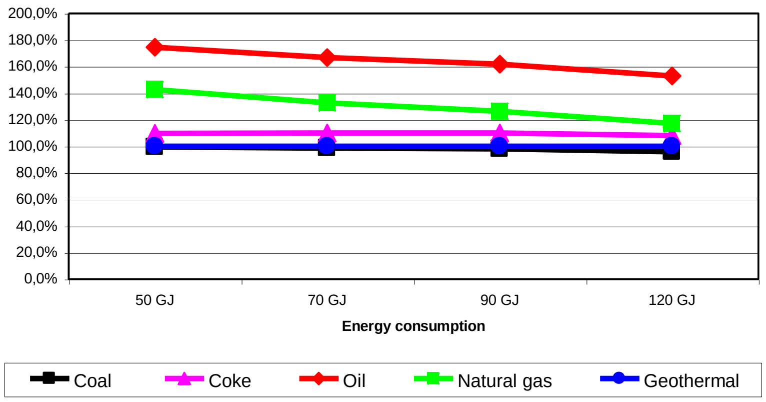


FIGURE 4.16: The Podhale geothermal heating system – cost comparison for small consumers (Dlugosz, 2003)

Besides heating, the residents and tourists look forward to developing the geothermal for multipurpose use covering a wide temperature range, especially as the heat price is expected to be lower in this case. The geothermal recreational and balneo-therapeutical centres are eagerly awaited in the Podhale region.

## 12. GEOTHERMAL ENERGY AS PART OF A STRATEGY OF SUSTAINABLE DEVELOPMENT OF THE PODHALE REGION

Geothermal energy is among the main natural resources in Podhale. It was made a part of local development strategy drawn up in recent years by local municipalities being regarded as 'strong points' of many localities. It appears as an attractive factor stimulating the development of tourism and recreation, new trends in agriculture, and the local employment market. In the case of Zakopane, the building of the geothermal space-heating network, and the bathing and balneotherapetical centre, are the priorities of the adopted development strategy.

The geothermal energy was planned to be implemented during the Winter Olympic Games for Zakopane, 2006 which Poland was competing for (Kepinska, 2002). A lot of attention, in accordance with the International Olympic Committee's requirements, was paid to environmental issues as well as a balanced approach in preparing and conducting the event. Investments that would assure clean air and water were to cause a permanent elimination of sources of the greatest ecological threats in Podhale. Extra flow of money was to remove the last obstacles to achieve the goals. Geothermal was assumed to play a leading role in pro-ecological programmes and activities. Extensive educational and promotional programmes on the protection of the environment and wide utilisation of local natural resources including geothermal were also planned. That would, in a way, prepare a clean environment for the Olympics. The geothermal energy was to heat the Olympic Village facilities, supply swimming pools and other recreational equipment, hotels and various sports buildings. The Olympic Village was planned to be constructed in downtown Zakopane, in close vicinity of two geothermal wells producing 26-36ºC water. The assumption was that the village would operate based on the symbiosis of local resources, geothermal energy, architecture and the beauty of the scenery. After the Olympics, the village would be used as a health and recreational resort.

Though Zakopane's application was rejected, some benefits of the campaign should be mentioned:

- The worldwide popularisation and promotion of geothermal energy. The Olympics would be a unique opportunity for promoting this ecologically clean energy among thousands of participants and a million worldwide spectators through mass media;
- Acceleration and development of research on geothermal resources in a particular country or region, progress in finding new methods and technologies and – last but not least – substantial increase of the flow of funds for geothermal research, projects and investments;
- Creating and developing high scientific and technical staff specialising in geothermal energy.

Fortunately, the idea of the Olympic application of geothermal energy will be implemented in China during the Summer Olympic Games in Beijing 2008. This most important sport event creates a great chance to take a real and valuable step in the field of geothermal development both in this country and in the world.

## 13. FURTHER PROSPECTS OF GEOTHERMAL USES

Apart from the district heating – essential for the ecological reasons, the other important applications of geothermal waiting for realisation for many years are balneotherapy and recreation. Due to chemical composition (i.e. $H_2S$, sulphides, bromine, iodine, potassium, silica), the Podhale geothermal waters have curative properties suitable in the dermatological, rheumatic, endocrinological and contagious diseases. Until 2001, only one geothermal bathing pool operated in Zakopane – the main town in the region. There are exceptionally great opportunities to build healing and recreational centres in this region. One of them is just being realised in Zakopane at the site of the existing pool. It includes the construction of the full range healing and recreational complex. This is a long expected project, indispensable to increase the tourist offerings and to improve the quality of recreation in this important tourist centre. For the Podhale region, geothermal balneotherapy and bathing appear to be very important chances for sustainable development of tourism and economics. Recently, the possibility of binary power generation started to be considered. This concept is based on over 90ºC water found in some wells.

## 14. CLOSING REMARKS

The Podhale geothermal system represents a very interesting and complex geological structure. Regarding the implementation of its low-enthalpy resources, it belongs to one of the most prospective in Europe. It offers very good reservoir and exploitation conditions – a basis for a large-scale geothermal space-heating network, and other multipurpose uses.

The geothermal space-heating project which is still underway, has already resulted in considerable ecological results expressed by significant reduction of emissions generated so far by huge amounts of coal burnt for heating purposes. Such reductions of gas and dust emissions would not be possible to achieve in a way different than the introduction of the geothermal system.

Further, project development will result in new and valuable scientific data. Ecological, social and economic benefits will prove the purposefulness, feasibility and reliability of using geothermal energy not only in Poland, but also in several other European countries, which possess geothermal aquifers connected with sedimentary systems.

# APPENDIX 1: GEOCHEMICAL AND RESERVOIR RESEARCH OF THE EXPLOITED SECTOR OF THE PODHALE GEOTHERMAL SYSTEM – SOME RESULTS

## 1. INTRODUCTION

Current exploitation of the Podhale geothermal system and further district heating project investments have been accompanied by investigation and monitoring. The aim is to get more and more detailed knowledge on the system in question, and to assure proper geothermal water production and project development.

This appendix presents some results of research work conducted for the exploited sector of the Podhale system where the wells IG-1, PGP-1, PAN-1 and PGP-2 are located (Figure 4.2). The various methods that were applied give new and interesting information on the past and present geothermal conditions. Some of the research was conducted under the framework of research grant no. 5T12B00822, funded by the State Committee for Scientific Research.

## 2. METHODS OF STUDY

As was mentioned in previous sections, high reservoir temperatures (up to 80-90°C), high water flowrates (up to 150 l/s), and high total and effective thickness of reservoir formation (up to 800 and 100 m, respectively) characterise the exploited sector of the Podhale geothermal system. Moreover, this sector is affected by deep faults, that favour intense fluid circulation and hydrothermal processes.

Regarding investigations of the low-enthalpy system in the sedimentary environment, being formed by the multi-staged process, both the classic geothermal methods and those used for the sedimentary basins including oil-perspective ones may be successfully applied. The results presented below were obtained using methods of geothermal geochemistry, X-ray analysis, fluid inclusions microthermometry, and also methods of studying thermal evolution of sedimentary basins, e.g. the thermal transformation of illite/smectite, and the evaluation of thermal organic matter maturity. The latter involves a new type of thermal analysis, the Oxyreactive Thermal Analysis (OTA; Cebulak et al., 1999). The methods described here, i.e. GC-MS, Rock-eval, Vitrinite reflectance and OTA bring much information for the investigations of the sedimentary basins and the geothermal systems connected with sedimentary rocks. Some of them are innovative in Podhale and even in Poland.

The research combines both cognitive and practical aspects to learn factors crucial for a geothermal system's evolution, as well as its exploitation and field development planning.

## 3. SELECTED FACTORS CONTROLLING THE PODHALE GEOTHERMAL SYSTEM

### 3.1 Temperatures

The present reservoir temperature reaches 80-90°C at a depth of 2-3 km. Figure A.1 shows the temperature in the vicinity of the Bialy Dunajec PAN-1 well. In the past, the maximum temperature of the Podhale flysch rocks and fluids amounted to 100-165°C. These values occurred in the early stage of the system lifetime, when the complex of the youngest flysch sediments, being at least 1-2 km thick, was not yet eroded. Then the geothermal gradient reached 3-4°C/100 m, while at present it is ca. 2°C/100m. Locally, in the near-fault zones (at a depth of 1850 m), the inclusions recorded temperature to 230°C. Chlorite and illite are also observed there. A similar effect is known from the Paris Basin,

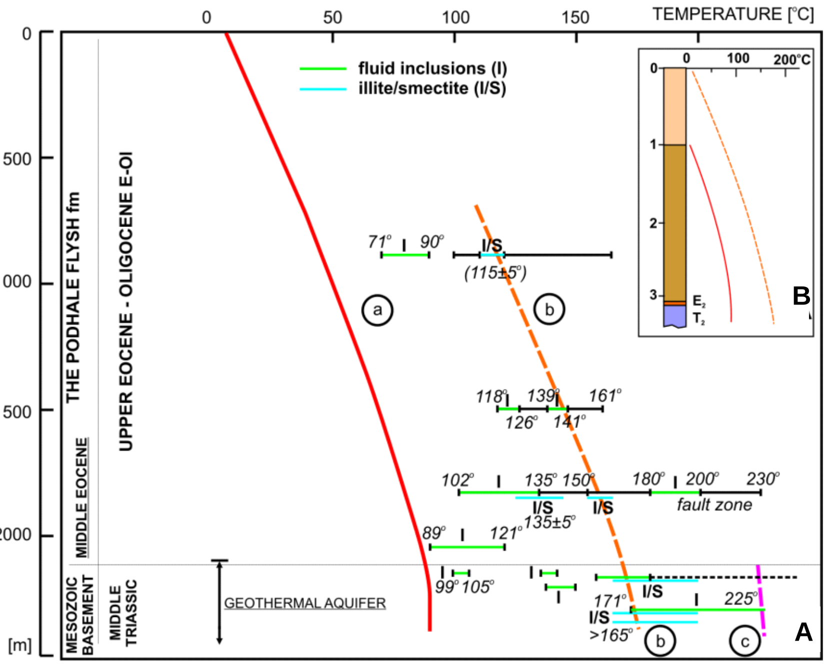


FIGURE A.1: The Podhale geothermal system – present and past subsurface temperatures, case of Bialy Dunajec PAN-1 well (based on Kepinska, 2001)

A. Temperatures shown against geological profile: a – present;
b – presumed maximum paleotemperatures (after Oligocene);
c – approximate paleotemperatures within the Middle Triassic rocks before the Upper Cretaceous orogenic movements. Figures mark the ranges of the fluid inclusion homogenisation temperatures (bolded are more frequent intervals); I/S – temperature ranges according to the illite-smectite group thermal transformation study; intermitted line shows temperature range in the Middle Triassic rocks (before alpine orogeny).
B. Temperatures shown against geological profile before erosion of ca. 1-2 km of flysch cover: a – present temperatures,
b – presumed paleotemperatures (as shown in A)

where the higher fluid inclusion homogenisation temperatures and more advanced illite/smectite thermal transformation occur in the fault zone than those in the area more distant from the faults (Bril et al., 1994). An example of a fluid inclusion from a hydrothermal calcite crystal formed in the Middle Triassic reservoir rocks from Podhale is shown in Figure A.2.

The maximum paleotemperatures of reservoir rocks and fluids reached a level of 200-230°C in the Middle Triassic. It concerns a period of their maximum burial before thrusting to the present location in the Late Cretaceous (the Alpine movements) and before the sedimentation of the Podhale flysch. After the Oligocene, i.e. after the Podhale system had been formed, the maximum temperature decreased to 165-170°C (Figure A.1). Such geothermometers as secondary quartz and dolomite, as well as the examination of the organic matter transformation degree including OTA also confirmed these ranges of the paleotemperature. Following from the above, the Podhale geothermal system has cooled down by at least 70-80°C during its lifetime (about 22 M.y.). Figure A.3a shows a sketch scenario of the thermal history of the Middle Triassic and Paleogene formations.

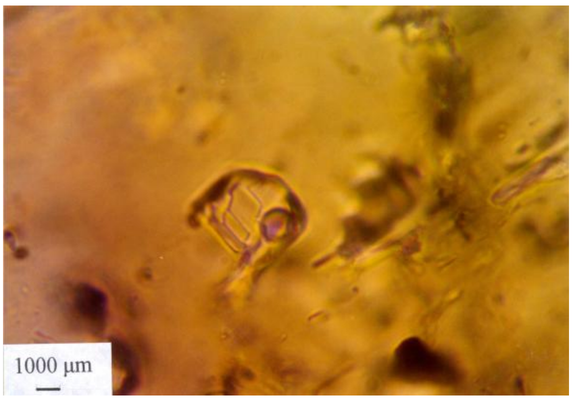


FIGURE A.2: An example of a fluid inclusion within a calcite crystal of hydrothermal origin from a secondary vein in reservoir dolomite in the Podhale geothermal system
(photo L. Karwowski)

### 3.2 Secondary mineralization

The secondary mineralization in the flysch caprock results mostly from diagenesis, while that in the Middle Triassic reservoir formation from hydrothermal processes. Secondary minerals filling veins and pockets, occur in the clay interbeddings, and replace primary minerals in the matrix. The secondary mineralization in the fractured Triassic rocks developed to a greater degree than that in the weakly permeable flysch (Figure A.4). Thermal transformations of illite/smectite and organic matter, which happened in the parent rocks of both formations, were independent from the rock permeability. The qualitative composition of the assemblages of secondary minerals within the veins both in the Paleogene and Middle Triassic formations does not differ essentially. Secondary calcite (sometimes dolomite) predominates both within the Paleogene flysch and the Middle Triassic rocks. Quartz, plagioclases, illite/smectite mixed-layers group, illite, Fe-chlorite, and pyrite occur as admixtures. In the Middle Triassic formation galena, gypsum, celestine, and sylwine are found in very minor amounts, too.

The illite/smectite mixed-layers serve as an important geothermometer for the Paleogene and the Middle Triassic rocks. The high degree of order (R1) and low content of the smectite layers in the flysch show that these rocks were affected by the paleotemperatures of 100-165°C. In the Middle Triassic rocks, a lack of the expending packages indicates the transformation being influenced by hot solutions or the temperature

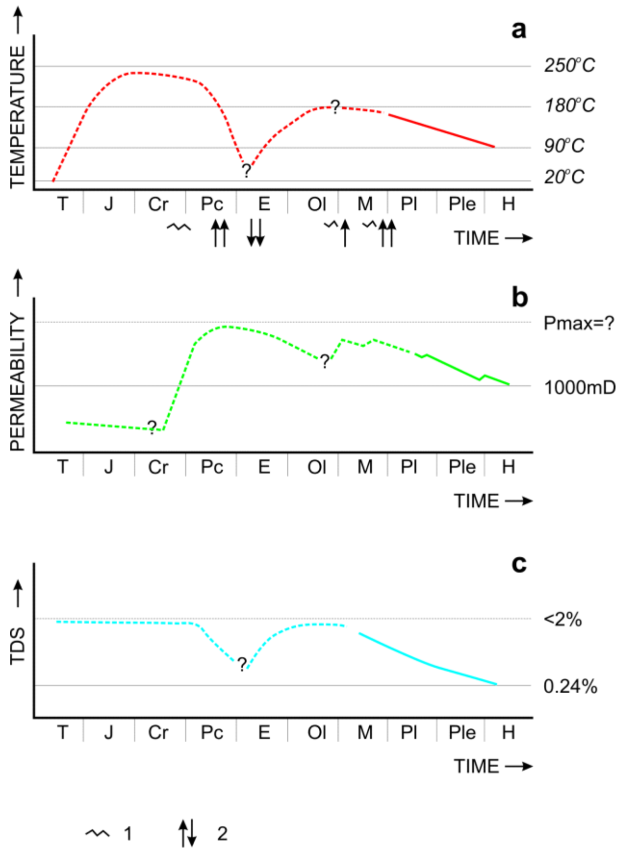


FIGURE A.3: The Podhale geothermal system, exploited sector – sketch scenarios of changes of the main parameters of the Middle Triassic reservoir rocks vs. geological time (Kepinska, 2001)
a. temperatures; b. secondary permeability; c. TDS of geothermal fluids. Presumed intervals of maximum temperatures and recorded present values are given. 1 – main stages of alpine orogeny, which affected the Middle Triassic rocks; 2 – lowering and uprising movements, respectively

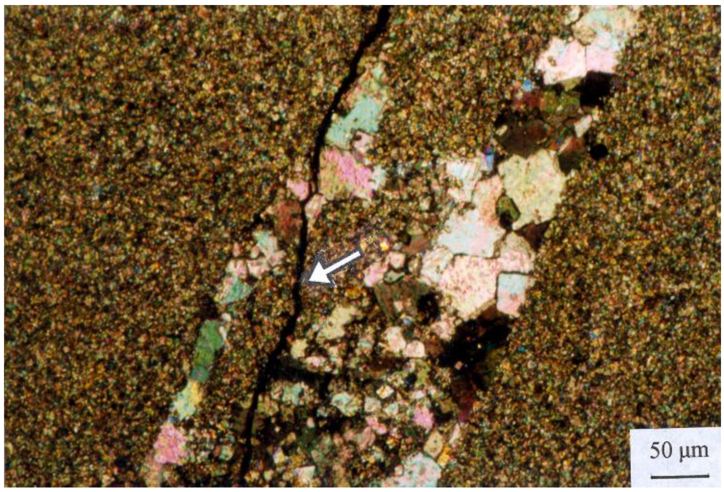


FIGURE A.4: An example of a vein in the Middle Triassic reservoir dolomite filled in with hydrothermal calcite, in the Podhale geothermal system. The youngest tectonic fissure is shown by an arrow (photo M. Pawlikowski) being higher than 165°C. Illite and chlorite might also precipitate directly from the solutions (Kepinska, 2001). Generally, the secondary mineral assemblages confirm the regularity (Browne, 1984), that the type of the hydrothermal mineralization in low–temperature systems is mainly controlled by the composition of parent rocks. In the case of the Podhale system, the predominant component of reservoir rocks – calcite, and sometimes dolomite, forms also secondary mineral assemblages.

The secondary mineralization results in a decrease of permeability of the reservoir rocks. In the past, the rocks passed through the periods of higher permeability with a probable maximum in the Paleocene - Early Eocene. It was after their thrusting in the Late Cretaceous, when they were uplifted, unstressed, outcropped, and affected by the karst processes. The second minor permeability maximum but concerning the geothermal system being already formed, may have occurred in the Miocene and was favoured by alpine vertical movements. Following this period, the progress in the secondary mineralization probably resulted in the decrease of permeability. Nevertheless, some fractures and breccia zones were weakly or not at all influenced by this process. The present permeability amounts to a maximum value of 1000 mD in the discussed sector, where the reservoir rocks are considerably fractured. A sketch scenario of permeability changes with time for the Middle Triassic rocks is given on Figure A.3b.

### 3.3 Chemistry and thermodynamics of geothermal water

The total dissolved solids of the geothermal waters amount to 2.5-3 g/dm$^3$. The waters are of Na-Ca-$SO_4$-Cl type. The calculations of thermodynamical water-mineral equilibria (using e.g. WATCH – program; Bjarnason, 1994) showed that these waters are not in equilibrium with the reservoir rocks. They are slightly oversaturated with calcite and dolomite, as well as clays (smectites and chlorites). In contrast, they are close to equilibrium with chalcedony and unsaturated with other minerals (Figure A.5). The waters are slightly corrosive against steel elements. In the course of their evolution, reservoir rocks contained both seawater (Middle Triassic – Cretaceous, Middle Eocene – Oligocene) and meteoric water (Late Cretaceous – Early Oligocene, Oligocene to the recent). Predominant content of calcite in veins of all origins proves that the past waters were also oversaturated with this mineral. Rough examination of the separate fluid inclusions revealed the paleofluid concentration not exceeding the concentration of the seawater. A sketch history scenario of the mineralization of the geothermal fluids for the Middle Triassic reservoir rocks is given on Figure A.3c.

## 4. IMPLICATIONS FOR EXPLOITATION

In particular, the scaling trend of calcite and dolomite exists. With time, the secondary minerals proceed in filling up fractures and fissures. Water is also oversaturated with smectites and chlorites. Though clays are found in small amounts, they may silt both the reservoir and the surface equipment. This effect may decrease the permeability of reservoir rocks. On the other hand, reciprocal processes, i.e. washing out and dissolving of rock components by water, occur. In spite of this, at the present stage of evolution, the Podhale system is still capable to discharge large amounts of water, especially in the zones affected by tectonics (the most perspective for siting new wells). The calcite scaling and corrosion tendency involves geothermal exploitation in the closed system. The scaling due to the secondary mineralization has also a positive effect, as it protects pipes thus decreasing their corrosion. In order to maintain stable production and injection capability of the reservoir rocks for a long time with scaling tendency being present, it is very advisable to perform periodical soft acidizing treatment to mitigate that effect. This has been successfully implemented in the Paris Basin (Ungemach, 1996; see also Lecture 2). It may limit scaling of carbonates and other components. This option is considered in the Podhale field, as it is more simple and cheaper than routine acidizing of the carbonates for increasing their production and injection capacity.

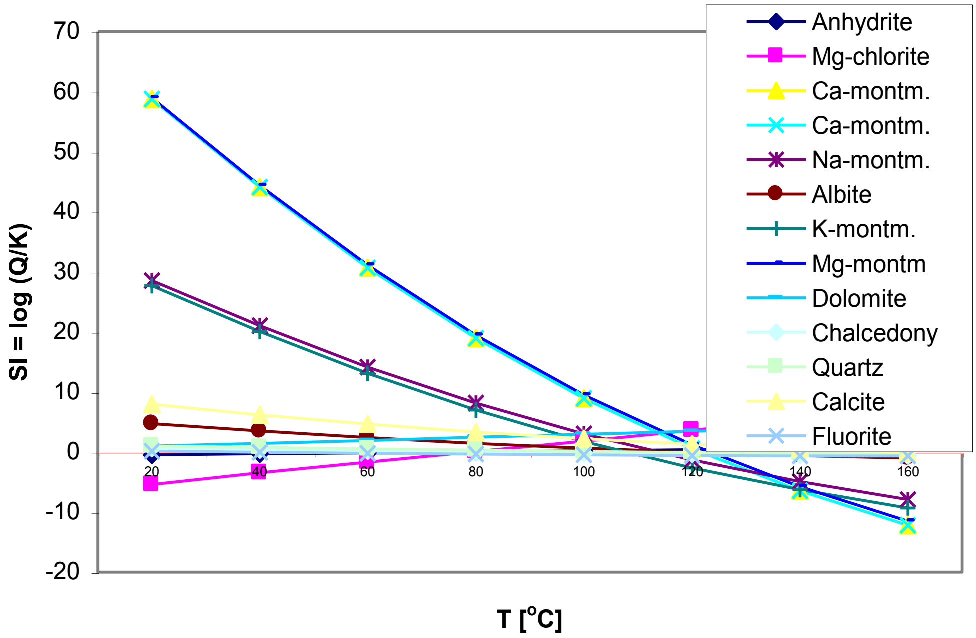


FIGURE A.5: Log (Q/K) water-mineral equilibrium diagram for geothermal water produced by Banska IG-1 well; calculations using the speciation program WATCH

## 5. CONCLUDING REMARKS

The age of the Podhale geothermal system is estimated to be about 22 Ma. The thermal apogee was in its past, when the temperature of rocks and circulated fluids reached at least a value of 165-170°C. With time, during the evolution the system was cooled down to a level of 80-90°C. Certainly, the permeability of the reservoir rocks reached its maximum value in the past, too. Since the Late Miocene filling of cracks and fractures has proceeded due to the secondary mineralization. Despite this, the system is still active, producing water at high flowrates and temperatures. The system offers very favourable conditions for space-heating and other multipurpose uses that gives the Podhale region the opportunity to introduce ecological and sustainable development strategy. The complementary application of both standard methods and those serving the study of geological and thermal evolution of sedimentary basins shown here are important for the recognition and management of this complex geothermal system.

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