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THE SUDETIC GEOTHERMAL REGION OF POLAND - NEW FINDINGS AND FURTHER PROSPECTS

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ABSTRACT
Natural springs of thermal waters are known in the Polish part of the Sudetes Mts at Cieplice and Lądek. Water temperatures in these springs amount to 44 °C and 29 °C respectively and bathing is the traditional water usage. Drilling performed during the last three decades revealed that considerable amounts of thermal waters occur in tectonically disturbed zones of Sudetic metamorphic rocks and granitoids. At Lądek the temperature of water spontaneously flowing out from the depth of 700 m reached 45 °C. At Cieplice the surface temperature of the outflow from 2000 m amounted to 87 °C. The measured bottom temperature exceeded 96 °C. As the circulation system was not reached, temperatures exceeding 100 °C may be expected at greater depths. This has been confirmed by chemical geothermometry. The existence of thermal waters may by also expected in numerous areas where carbonated waters occur. CO_2 connected with Late Tertiary and Early Quaternary basic magmatism may be an indicator of regional rock heating at relatively shallow depths. Its expansion causes the cooling of waters circulating near the surface, but deeper horizons may be the reservoir of thermal waters. A program of exploratory drilling down to 1500-2000 m has been established for Polanica, Duszniki, Kudowa (within or in the immediate surroundings of the Intra-Sudetic Trough) and for Świeradów-Czerniawa (the Karkonosze-Izera Block). In case of success the region will get new resources of clean, cheap energy. Another potential area is the Fore-Sudetic Block, where thermal carbonated water was discovered in the vicinity of a basalt outcrops cluster and where Tertiary hydrothermal processes have been documented.

1. INTRODUCTION

The Sudetic region in SW Poland including the Sudetes Mts and the Fore-Sudetic Block limited to the NE by the Odra fault (Fig. 1) is an exception as compared to the rest of Poland's geological setting. Instead of large sedimentary basins of the Polish Lowland and the Carpathian foredeep or folded flysch formations of the external Carpathians, the Sudetes Mts consist mainly of old crystalline rocks covered with younger sediments. Precambrian and Lower Palaeozoic gneisses and schists with not uncommon marble intercalations were intruded by Upper Carboniferous granitoids which form among others the core of the Karkonosze-Izera massif. In synclinal structures the crystalline rocks are covered with Phanerozoic sediments (Silurian-Quaternary). Intensive Variscan and Alpine movements which took place in many tectonic phases until at least the Late Tertiary resulted in a complicated structure typical of horsts and grabens, often secondarily folded and dissected by faults and flexures. The Tertiary tectonic movements are responsible for the separation of the Sudetes and the Fore-Sudetic block. The demarcation line is the NW-SE running Sudetic border fault of which the Sudetes form the hanging side. Geological features as for example the presence of old metamorphic and igneous rocks or the Cenozoic basaltic volcanism are similar on both sides of the fault. Mountains on the SW side of the border fault allow more intense and deeper circulation of meteoric waters within the crystalline formations. On the down side of the fault these formations are mostly covered with Cretaceous and Tertiary sediments.

The Tertiary tectonics, which often rejuvenated older dislocations contributed to rock fissurization and more intense ground water circulation. In particular, in higher parts of the Sudetes Mts the faulting allows deep penetration of meteoric waters. As shown by the recent drilling results at Cieplice, the depth of circulation may, in favourable circumstances, exceed 2000 m (Dowgiałło, 1999).

Studies on the hydrogeology of thermal waters were for years limited to their known occurrences at the thermal spas of Cieplice and Lądek. New findings, mostly accidental, call attention to the whole region as a hydrogeothermally promising one.

2. GENERAL GEOTHERMAL CHARACTERISTICS OF THE SUDETIC REGION

The knowledge of the geothermal field in SW Poland was poor until quite lately. The only heat flow density measurement in the Sudetes Mts was done in Lądek (Ćermak, 1974, Dowgiallo, 1976). A more detailed geothermal survey was done in the Czech territory, SW of the Polish Sudetes Mts (Ćermak and ®afanda, 1982) and on the Fore-Sudetic Monocline bordering the Sudetic region to the NE along the Odra fault (Plewa, 1994).

A recent paper by Bruszewska (1999) fills the gap. For the Sudetic region, it is based on 25 bore holes of various depths and on measurements mostly of high credibility. The measuring points, however, are distributed unevenly. In some parts of the Sudetes Mts the lack of measurements forced the quoted author to adopt heat flow values presented in Hurtig, ed, (1992). Large areas without data have to be noticed on the Fore-Sudetic Block. Due to these deficiencies some areas on the maps of heat flow density, temperature at different depths and temperature gradients are of lesser credibility. Nevertheless, the general picture is in some agreement with the main geological features of the region (e.g. faults of regional importance).

The heat flow density values on the map (Bruszewska, 1999) range within the Sudetic region of Poland between 50 and 65 mWm^{-2} (Fig. 1). These values are not sufficiently substantiated everywhere.

The paper by Bruszewska (1999) does not include a table showing heat flow density (HFD) values determined in particular boreholes and used for the construction of the map. Therefore Fig. 1 includes only 5 points for which HFD values have been known earlier: Lądek, Dzikowiec IG I, Unisław Śląski IG I, Niedźwiedź IG II, Cieplice C-1 (Tab. 1). The HFD values obtained in the quoted boreholes are relatively high as compared with isolines on the map, except the Niedźwiedź borehole. It must be pointed out that no clear coincidence has been found so far between the heat flow density and the occurrences of basalt, some of which are of Quaternary age (Birkenmajer et al., 1970; Wroński, 1970). Values found for areas where groups of basalt outcrops are noted (e.g. the Grabin area) do not exceed 65 mWm^{-2} (Bruszewska 1999). The reason for that is probably the fact that surface extrusions of basaltic lavas favour fast heat dissipation. Therefore drillings in which measurements were done (less than 1000 m depth) do not show any distinct anomaly.

Although HFD values exceeding the average have not until now been recorded in the Sudetes Mts (outside of thermal water outflow zones) this is not a proof of their nonexistence. The possibility of high densities of the heat flow conductive component is indicated by the high content of radioactive elements in some crystalline formations and the resulting production of radiogenic heat.

Among formations particularly enriched in uranium and thorium, the Carboniferous Karkonosze granite and other Sudetic granites should be quoted. According to Jeliński (1965) the content of uranium in the Karkonosze granite is typically 12-15 g/t, sometimes amounting to 75 g/t, while the average values for granites do not exceed 3.5 g/t (R sler and Lange, 1972). The thorium content is high too (20-25 g/t, sometimes exceeding 50 g/t), while its average content in granites is 18 g/t. The radiogenic heat production amounts here up to 5 $:Wm^{-3}$ (Plewa, 1994). Taking into account the thickness of the granitic body (several km) this should be reflected in the HFD. High content of radioactive elements in the Karkonosze granite has also been found on the Czech side of the border (Matolin, 1979). Gneisses older than the Sudetic granites are also rich in uranium and for instance its content in the Śnieźnik gneisses (Lądek area) is 11,3 g/t (Przeniosło, 1970). The total radiogenic heat generated in an average granite contributes to the mantle heat flow density by 2,5 mWm^{-2} per 1 km of granite thickness (Rybach, 1976). In the case of the Carbonifeous Sudetic granites and probably, also of some older formations intruded by these granites this coefficient is certtainly higher. The obvious fact has also to be pointed out that the occurrence of granites is not limited to the areas where they became exposed due to erosion and that under the cover of older rocks they occupy considerably larger areas.

The possibility of the existence of positive geothermal anomalies in the Sudetes is also suggested by the presence of Late Tertiary or even Quaternary basaltic effusions and veins. This testifies to a quite late strong warming of the region by magma mobilized during tectonic movements. Relatively shallow magma traps may still exist within the basement (Elder, 1981) and may contribute to the heat flow density.

The occurrence of neovolcanites is not known in the area of the Intra-Sudetic Synclinorium. This does not mean, however, that post-Laramian mobilization and transport of basaltic magma did not take place there. Its rise to the surface must have been hindered by compression within the synclinorium (Oberc, 1972). Young (Pliocene-Lower Pleistocene) basaltic volcanoes appear, anyway, in the adjacent area (the Lądek-Śnieźnik metamorphic massif). The lack of Neogene-Quaternary volcanism within the Intra-Sudetic synclinorium is advantageous as far as geothermal resources are concerned. Volcanic eruptions did not cause the loss of heat brought from the depths. Low viscosity of basaltic magma is the reason for its high mobility and facilitates its displacement in rock fissures to considerable distances and its cooling in contact with the rock. If, however, tectonic factors preclude magma from migrating in rocks and its effusion at the surface, it may conserve the high temperature, thus contributing to the heat flow density. The Intra-Sudetic Synclinorium may then be considered as one of the areas in which positive geothermal anomalies, unknown until now, may occur. Carbon dioxide occurring in considerable amounts in many Sudetic groundwaters is, according to a generally adopted opinion, linked to magmatic phenomena discussed above. It migrates through deep-seated dislocation zones, particularly in their intersection points. Causing the increase of ground waters mineralization it gives them therapeutic properties due to which a number of health resorts (Świeradów, Czerniawa, Szczawno, Duszniki, Kudowa, Polanica, Długopole) have developed. The presence of carbon dioxide may testify to the existence of cooling magma beneath a given area.

3. REVIEW OF SELECTED GEOTHERMAL SYSTEMS IN THE SUDETIC REGION

A number of hydrogeothermal systems have been distinguished in the Sudetes Mts both on the Polish and Czech sides of the border. Their general descriptions may be found in Dowgiałło (1976, 1991). The present paper deals entirely with the Polish territory, including the Fore-Sudetic block. Well-defined hydrogeothermal systems, individual points in which thermal waters have been struck as well as young hydrothermal phenomena were taken into consideration. The temperature of 20 ^oC was adopted as the minimum for water flowing at the surface from a spring or borehole. This internationally recognized value allows to clearly distinguish thermal waters from fresh groundwater.

3.1. Defined hydrogeothermal systems.

Cieplice

The renowned thermal spa of Cieplice is certainly the most important thermal water occurrence in the Sudetic region. Situated near the city of Jelenia Góra, it belongs to the Jelenia Góra geothermal system described in detail by Dowgiałło and Fistek 1995).

The use of thermal water from natural springs for therapeutic purposes was noted as early as the 14th century and a famous health resort developed here in the 17-19th centuries. The temperature of spring water (up to 44 ^oC) is the highest ever found in the Sudetes in natural ouflows. During years 1971-1972 two drillings have been carried out (C-1, depth 661 m, C-2 depth 750 m). They revealed considerable amounts of thermal water below 700 m. The yield of spontaneous outflow from the borehole C-2 amounted to 40 m^3/h with pressure at the closed wellhead reaching 2.5 atm). This yield exceeded by several times the total yield of natural thermal springs. The highest water temperature observed at the outflow was 68 ^oC while on the average it was close to 59 ^oC.

The need for additional amounts of thermal water for treatments and space heating lead to the decision to deepen the C-1 borehole. This has been done up to the depth of 2002 m and brought positive results (Dowgiałło and Fistek 1998, Dowgiałło, 1999). The spontaneous outflow from the depth below 1600 m was 88 m^3/h, the pressure at closed wellhead being 3 atm (immediately after the drilling was finished). The temperature of water flowing at the surface amounted to 87.6^o

C while the thermal log has shown the bottom temperature 96^o C and 97.7 ^{o}C at the depth of 1870 m. After several months of well testing the water temperature at the outflow stabilized at 86.7 ^{o} C and the yield decreased to 45 m^3/h, which is probably the sustainable value. The pressure at closed wellhead is stabilizing at 1.4 atm.

The host aquifer is predominantly a monzonitic granite or granodiorite cut by basic veins of lamprophyre type. The water chemistry is extremely homogenous at all depths of its occurrence. From the surface up to the deepest inflow those are waters of the SO_4-HCO_3-Na^+ + F + Si type with TDS close to 650 ppm.

There is an obvious hydraulic contact between all water-bearing zones intersected. The tests carried out in the borehole C-1 have caused a considerable drawdown in the C-2 borehole as well as the vanishing of two natural springs which yielded the warmest water (No 5 and 6).

Some indicators of thermal water presence such as increased shallow water temperatures and a relatively high geothermal gradient in shallow boreholes have been found in several parts of the Jelenia Góra basin (Fig. 2). This suggests the possibility of finding additional thermal water amounts in areas West, North and East of Cieplice.

Theories concerning the position of the recharge zone of deep circulating thermal waters are contradictory. The discussion summarized and continued by Ciężkowski et al. (1992) as well as by Dowgiałło and Fistek (1995) is not yet settled. Isotope data indicate that the recharge took place either in a cooler climatic period (Pleistocene?) or at considerable altitudes. According to the present author the most probable recharge zone for thermal waters are the NE slopes of the main Karkonosze range, especially the Pogórze Karkonoskie plateau (altitudes 900-700 m). The chemical composition of thermal waters and calculated thermodynamic equilibria between water and rock-forming minerals (Dowgiałło et al., 1989) suggest that the Jelenia Góra geothermal system is altogether limited to the Karkonosze granite occurrence. A considerable role in the circulation system seems to be played by the Karkonosze marginal fault separating the Karkonosze foothills from the Jelenia Góra morphological basin. Some recharge of the hydrogeothermal system from the Rudawy Janowickie Mts (East of Cieplice) might be facilitated through this important fault zone.

Duszniki

The natural CO_2-rich mineral waters at Duszniki originally flowed artesian. Later wells have been drilled, to exploit the resource. Their depth did not exceed 170 m. The temperature of water flowing spontaneously from some wells immediately after their completion in 1910 was close to, or even higher than, 20 ^{o}C. At present it sometimes exceeds 18 ^{o}C. It would doubtless be higher by several degrees (1.5-7 ^{o}C) if cooling caused by expanding carbon-dioxide did not take place (Dowgiałło, 1987). Also inflows of cool, tritium rich waters are clearly marked on the wells thermal logs. Chemical geothermometers indicate temperatures around 90 ^{o}C in the deeper parts of the system.

The Duszniki geothermal system is hosted in the Proterozoic series of micaschists with marble intercalations. The recharge area is situated S and SW of Duszniki, on the SE slopes of the Orlickie Mts. The discharge area in the Bystrzyca Dusznicka R. valley is connected with a system of faults, transverse to the important tectonic zone Pstrążna-Gorzanów confining from the SW the Intra-Sudetic Synclinorium (Fistek, 1989).

Kudowa

The outflow of thermal water (20.5 ^{o}C) from a 120 m deep drill hole occurred at Jeleniów near Kudowa. High temperatures indicated, although not unequivocally, by chemical geothermometers in the Kudowa mineral carbonated waters suggest the presence of a geothermal system (Dowgiallo, 1987). Its recharge area is probably situated within the granitic massif located east of Kudowa. The discharge zone, instead, is connected with faults dividing the tectonic depression of Kudowa into particular blocks.

Lądek

Thermal waters at Lądek with a TDS around 200 mg/l, are hosted in the Proterozoic or Early Palaeozoic Śnieżnik and Gierałtów gneisses. Water temperatures in natural springs do not exceed 29 ^{o}C. A 700 m drill hole completed in 1973 supplies water flowing spontaneously with a temperature of 45 ^{o}C, its present yield amounting to 30 m^3/h. Immediately after the drilling was completed, the well yielded 100 m^3/h, with a clear negative influence upon the yield of natural springs.

Water temperatures of the Lądek thermal springs, being much lower than in the drill hole and the presence of some tritium, testify to the admixtures of cool waters of shallow circulation. The chemical composition of the Lądek thermal waters is little differentiated, which shows that these admixtures do not influence considerably the equilibrium ionic ratios established in the lower part of the system. Geothermometric calculations suggest that temperatures there may have attained 70 ^{o}C.

The previous workers have placed the recharge area of the Lądek geothermal system in the upper parts of the Złote Mts and Bialskie Mts, S and SE of Lądek (Dowgiałło, 1976; Ciężkowski, 1980). Zuber et al. (1995) basing on isotope and noble gas measurements, propose to limit the recharge area to the Bialskie Mts., at altitudes exceeding 700 m.

3.2. Punctual occurrences of thermal waters

Turoszów

Within the brown-coal open-cast "Turów" a sudden outflow of thermal water took place in 1981. The recorded temperature was 27 ^{o}C, and the yield was 8 m^3/h (Sztuk, 1986). The TDS of the water was 4 g/l, it contained also 14.5 mg/dm^3 of F^- and traces of free CO_2 (0.2 mg/dm^3). The water comes from a fault zone within the pre-Variscan Rumburk granite forming the basement of the Zittau (FRG) - Turoszów basin filled with Tertiary sediments. The tectonic zone of N-S direction forming the Western margin of the Karkonosze-Izera crystalline massif is accompanied by numerous basalts and related rocks occurrences of Late Tertiary.

Grabin

A test hole to the depth of 545 m has been carried out in 1983 at Grabin, near Niemodlin (Fore-Sudetic Block). Under Quaternary, Tertiary and Cretaceous formations the crystalline basement (paragneisses) was encountered at 485 m (Morawski and Sawicki, 1984). From a fault zone an important outflow of thermal water oversaturated with CO_2 took place. Its temperature is 31.4 ^{o}C, TDS amounts to 9.8 g/dm^3. The water of the chemical type HCO_3-Na-Mg-Ca contains 110 mg/dm^3

free CO_2, 110.5 mg/dm^3 H_2SiO_3 and 2.7 mg/dm^3 HBO_2. The yield of the outflow amounted to 200 m^3/h (Hordejuk and Płochniewski, 1986). These results were confirmed during new tests performed in 1990 (Czerski and Wojtkowiak, 1991). The maximum yield after seven years dropped, however, to 157.5 m^3/h.

It has to be pointed out that near Niemodlin Tertiary basalts occur in several sites. The connection of the water CO_2 content and its temperature with Tertiary volcanism seems to be obvious. The finding at Grabin encourages hydrogeothermal prospecting in the Fore-Sudetic Block. A program of drilling preceded by regional geophysical prospecting is to be carried out in this area, particularly where clusters of basalt outcrops occur.

3.3. Cenozoic hydrothermal phenomena

The Late Tertiary and Quaternary magmatic activity caused hydrothermal phenomena in some parts of the Fore-Sudetic Block. At Dębowiec (S of Strzelin) a basalt eruption of Pleistocene age has been documented (Wroński 1970). Ten km to NNE at Przeworno a cave has been found with a siliceous flowstone (sinter) deposit. According to Galewski and Głazek (1973) this is a precipitate of hot water oversaturated with silica, certainly linked with the young volcanism. The flowstone contains Coleoptera fauna, which could be of Quaternary age. The above-mentioned authors suggest also that the hot water presence coincided with an extensive hydrothermal kaolinization of metamorphic rocks and rock-crystal formation in the neighbouring Jegłowa.

Another area where hydrothermal processes took place is the vicinity of Kliczków and Osiecznica. Middle Miocene sands are here silicified, probably by silica precipitated from thermal water. This process was only slightly younger than the sedimentation of sands. The migration of hot water was connected with faults of the NW-SE and NE-SW directions and in particular with their crossings (Oberc and Dyjor 1971).

4. CONCLUSIONS

Both the Sudetes Mts and the Fore-Sudetic Block deserve the qualification of a particular geothermal region with two distinct subregions. Most of the fragmentary hydrogeothermal investigations carried out until now in the Polish part of the Sudetes Mts were limited to zones of occurrence of thermal waters utilized for therapeutic purposes or to few areas where prospecting for such waters was carried out (e.g. the Jelenia Góra basin). As such prospecting is supposed to intensify in the future, the number of identified geothermal systems will increase. This is corroborated by fortuitous discoveries of thermal waters (e.g. at Turoszów). The occurrence of geothermal systems within the Sudetic Mts crystalline formations is favoured by:

- possible high heat flow densities, caused by Cenozoic volcanism and radiogenic heat
- considerable altitude differences enabling meteoric waters to penetrate deeply and to flow out in drainage zones situated in morphologic depressions;
- a dense system of fissures and joints accompanying faults which originate from, or were renewed in, the period of post-Laramian movements. Zones of such fissures are the main circulation paths for groundwaters, including thermal waters,
- the presence of horizontal or almost horizontal relaxation joints due to the deep erosion of the Sudetic horst, upheaved in the Late Tertiary and to the relief of previously deep-seated rocks. Such joints are particularly typical of the Karkonosze granite where they have been described by Cloos (1925).

Insufficient resources of deeply circulating meteoric water may be the factor limiting the possibilities of practical utilization of the Sudetic geothermal systems. These resources depend not only on the amount of atmospheric precipitation but also on the surface runoff which plays a considerable role in the water balance of the area. The Fore-Sudetic Block is certainly worth intensive investigations. Water infiltrating in the Sudetes Mts is recharging deep groundwaters in this sub-region. The volcanic manifestations are also a promising feature for hydrogeothermal prospecting.

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Table 1.
Published heat flow density values in the Polish Sudetic region.

Locality/borehole	HFD (mWm^{-2})	Author
Lądek 2	71.2	Dowgiałło 1976
Dzikowiec IG I	63.2	Plewa et al., (1995)
Unisław Śl. IG I	62.6	Plewa et al., (1995)
Cieplice C-1	79	Dowgiałło 1999
Niedźwiedź IG II	46.6	Plewa et al., (1995)

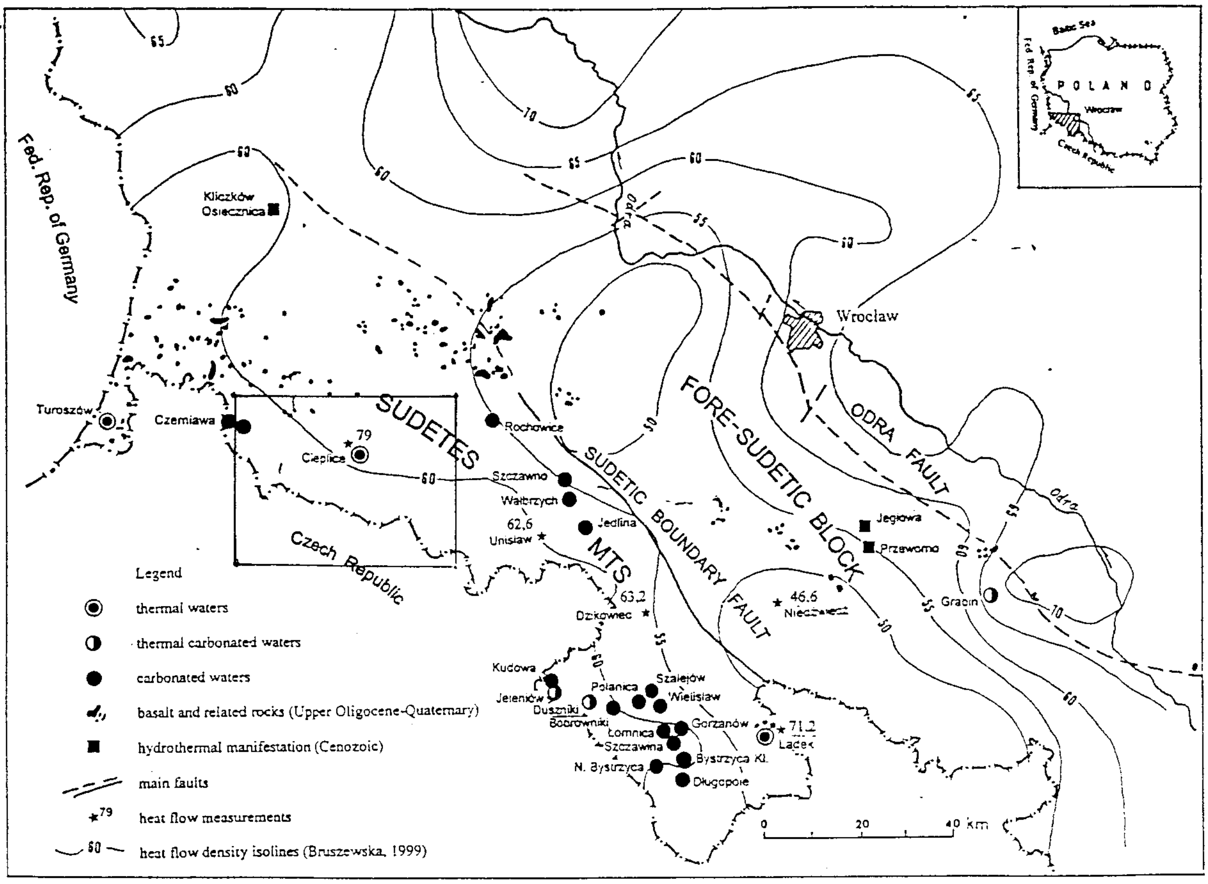

Figure 1. Selected Features of the Sudetic Geothermal Region

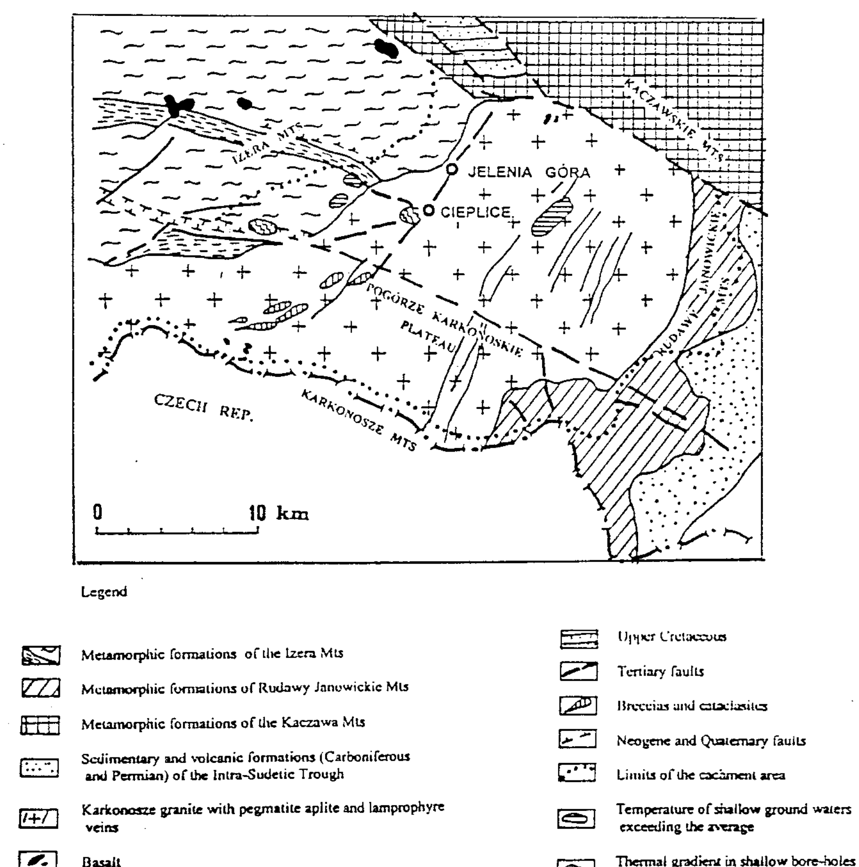

Figure 2. Geological sketch of the Jelenia Góra-Cieplice basin and its surroundings