*In memoriam*
*Professor Wojciech Jaroszewski*
*and*
*Doctor Stanisław Kibitlewski,*
*who were excellent scientists*
*and high-minded people*

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# THE SILESIAN-CRACOW Zn-Pb DEPOSITS, POLAND: CONSIDERATIONS ON ORE-FORMING PROCESSES

(with 12 Figs.)

*Abstract.* The position of the Silesian-Cracow deposits was presented on the background of the geologic structure of the hosting area. The connection of the ore mineralization with the disjunctive tectonics was shown. The special intensity of the ore mineralization was stated in association with the graben structures, generated by regional faults of the strike-slip nature. Post-Jurassic age of these tectonic structures determined thus the age of the deposit-type concentration of ores as Cretaceous to Tertiary. Dynamics of the tectonic processes (compressional and tensional) affected the flow of mineral-forming solutions and ore concentrations. Analysis of the tectonic structures proved the influence of the fault network of the deep basement on development of the Zn-Pb deposits. The results of the fluid inclusion studies were used to construct the pattern of the ore-forming fluid flow, that is consistent with the observed tectonic peculiarities. The Silesian-Cracow deposits are compared with other carbonate-hosted Zn-Pb deposits, with special attention paid to the Mississippi Valley-type, and in conclusion it is not recommended to include the Polish deposits to this type because of important genetic differences.

*Key words:* Poland, Silesian-Cracow area, Zn-Pb sulfides, carbonate-hosted deposits, Mississippi Valley-type, tectonic control, fluid migration, fluid inclusions, ore-forming processes.

## INTRODUCTION

The Zn-Pb deposits of the Silesian-Cracow area have been investigated since many years, however, there is no agreement about their basic genetic problems, i.e. the source (or sources) of the ore substance and mechanism of migration of ore-forming solutions. The elaborations lack, that would conclude the complete problem, taking into account considerations based on the data, which resulted from the present-day knowledge on tectonics of the Silesian-Cracow area.

The performed studies and the analysis of the publications, concerning the subject of the investigation, suggested that the tectonic control was the most important factor of development and concentration of ores in the Silesian-Cracow area. The tectonic structures (especially

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those deep-seated and of durable tectonic activity), being simultaneously indices of locally variable conditions of stress in a rock massif, displayed the solving role in determination of the flow paths of hydrothermal ore-forming solutions and sites of the ore precipitation.

The results of the studies may be of practical importance in prospecting and exploitation works, making possible the prognosing of locations of high concentrations of the Zn-Pb ores.

## REGIONAL BACKGROUND

The Silesian-Cracow Zn-Pb deposits occur in the border zone of Bohemian Massif (Fig. 1). This tectonically complicated area, called also the Cracow–Myszków or Cracow–Lubliniec zone, of the width of few to more than ten km and of the NW–SE extension, occurs at the junction of two regional tectonic units: Upper Silesian Block in the east and Małopolska Block in the west. These blocks formed in Precambrian, are considered as microcontinents or terranes (S. Bukowy, 1984; C. Harańczyk, 1994; Z. Buła, 1994; J. Żaba, 1995). The Cracow–Myszków zone is a part of a large-scale discontinuity zone, formed most probably in Proterozoic (Z. Buła, 1994). This zone in the north turns to WNW and extends along the northern border of Bohemian Massif (transcontinental

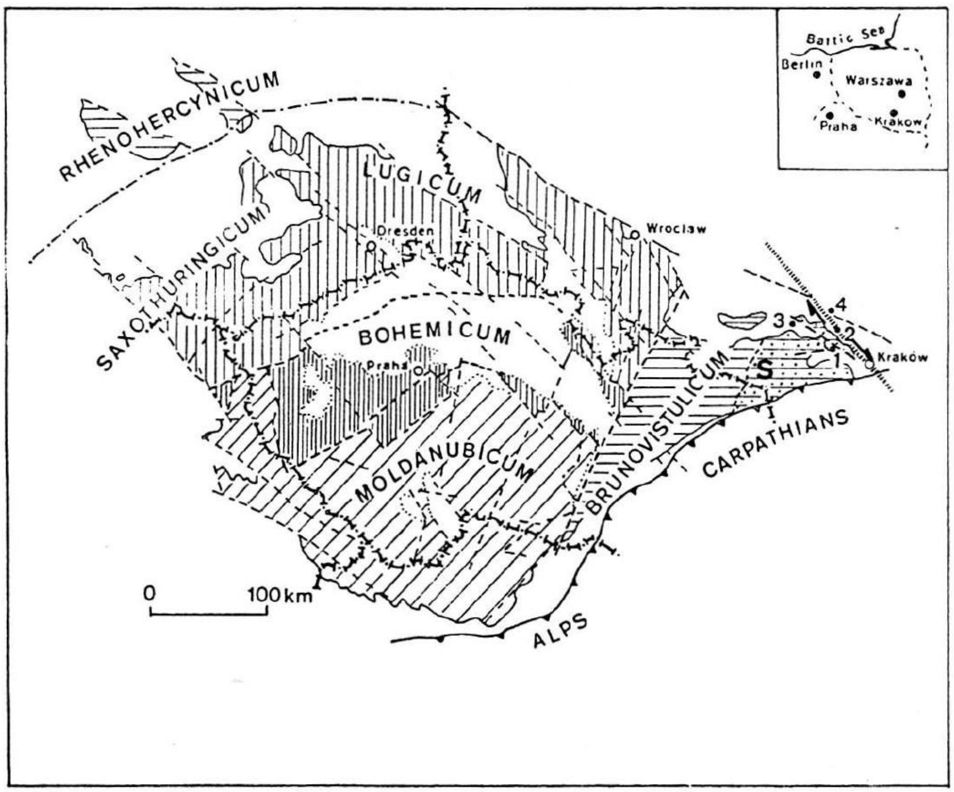



Fig. 1. Location of the Silesian-Cracow Zn-Pb deposits in relation to the Bohemian Massif (tectonic sketch map after J. Chaloupský, 1989)

Lined areas — Variscan massifs; S — Upper Silesian Block; the heavy line with arrows, showing the principal direction and sense of the strike-slip movements, marks a fragment of the Szczecin–Cracow–Prešov transcontinental fault zone (after J. Żaba, 1995); Zn-Pb deposits (marked by the present authors): 1 — Chrzanów district, 2 — Olkusz district, 3 — Bytom district, 4 — Zawiercie area

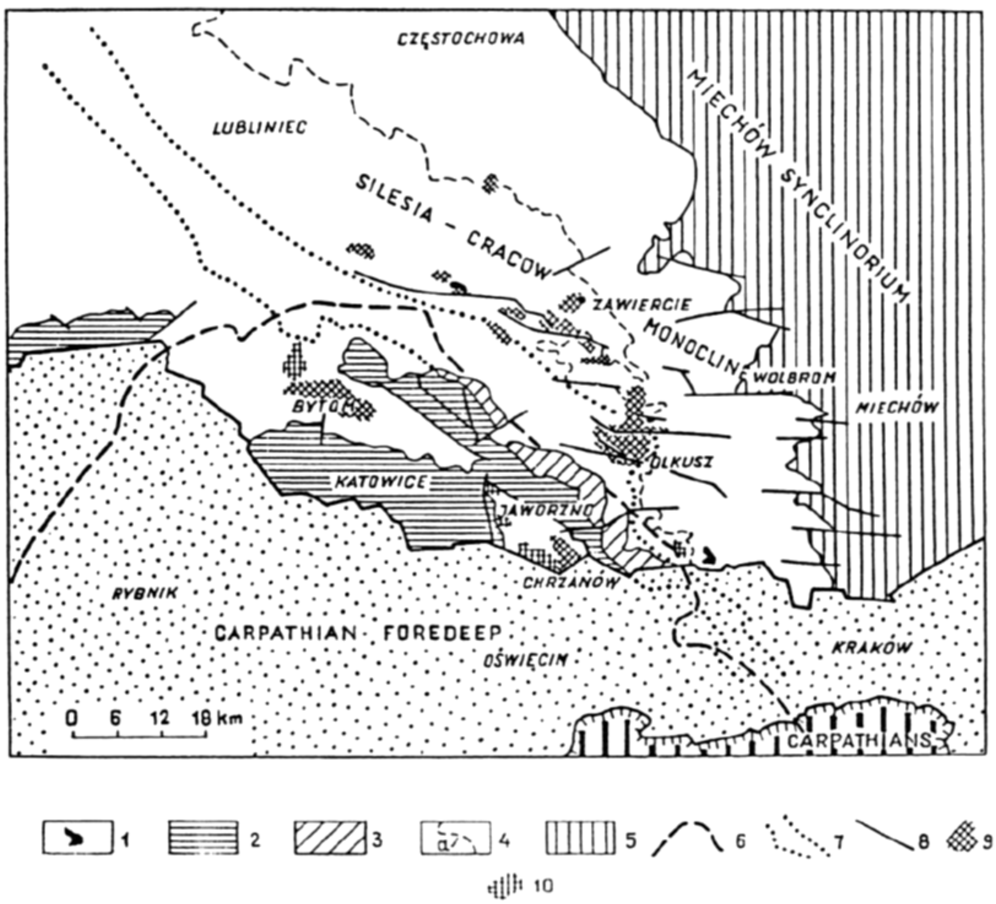



Fig. 2. Distribution of the main Zn-Pb deposits in the Silesian-Cracow area (geology after S. Bukowy, 1974; Zn-Pb deposits after E. Górecka, 1993a)

*1* — Devonian, *2* — Carboniferous, *3* — Permian, *4* — Triassic and Jurassic (*a* — Jurassic boundary), *5* — Cretaceous, *6* — boundary of Upper Silesian Coal Basin, *7* — extent of Permian graben, *8* — faults, *9* — Zn-Pb deposits (proved and mined), *10* — exhausted Zn-Pb deposits

fault zone Hamburg–Berlin–Wrocław). In the environs of Cracow this tectonic zone is buried under the front of the Carpathian overthrust. Moreover, J. Żaba (1995) distinguished another transcontinental fault zone Szczecin–Cracow–Prešov, which in the section Cracow–Myszków almost coincides with the above-named fault zone. According to the latter author, the second transcontinental fault zone, occurring close to the NE margin of the Upper Silesian Block, formed in Upper Carboniferous (after Namurian A) due to steep thrusting of the NE part of the Upper Silesian Block on the edge of the Małopolska Block under conditions of the right strike-slip transpression. Paleomagnetic studies of the Devonian and Carboniferous rocks from the Cracow–Myszków zone indicated, that the strike-slip movements did not exceed several tens kilometres (J. Nawrocki, 1993). Later, and probably till present, movements of the strike- and dip-slip type occurred along this geosuture zone several times.

The durable tectonic activity in the Cracow–Myszków zone had an influence on the multistage structural evolution of the geologic formations, occurring in this area (see E. Górecka, 1993a). Results of the studies, published by numerous authors, indicate the two-fold geologic structure of Paleozoic formation of this area. Differences in lithological and facial features, and in tectonic deformations of the Early Paleozoic sediments, occurring on the both sides of the regional dislocation zone, are apparent here. On the western side of the zone, directly on the

Upper Silesian Block, the Early Paleozoic sediments consist only of the clastic Cambrian beds. On the eastern side, in the marginal part of the Małopolska Block, one found strongly tectonised complexes of clastic and carbonate rocks of Cambrian, Ordovician and Silurian age, usually determined as Caledonian Krakovides orogen.

In these two regions the Early Paleozoic deposits were discordantly overlaid by Epicaledonian platform cover built of mainly carbonate Devonian and Lower Carboniferous sediments. Upper Carboniferous (Namurian and Westphalian) formed in the area of the Upper Silesian Basin coal measures of great thickness (Fig. 2).

In the Cracow–Myszków zone, the folded-blocky Variscan tectonics rebuilt and obliterated to a considerable degree the older structures of imperfectly consolidated Caledonian orogen. In the deep-seated discontinuity zone, bordering the Upper Silesian Coal Basin, the platform pattern of the late Variscan tectonics was represented by a fold or brachyfold system. Those folds of the prevailing strike close to a parallel of latitude, were cut by multidirectional network of faults. Anticlines were formed from the Devonian and Carboniferous rocks, whereas synclines from the Lower Carboniferous ones. Upper Carboniferous, mainly Namurian sediments, occur locally in depressed structures.

A similar style of the Variscan tectonics, i.e. generally meridional orientation and perpendicular one to the latter for the important folded structures, consisting of flat elevations and depressions cut by the fault network, is possible to observe in the central and eastern parts of the Upper Silesian Coal Basin. One may distinguish the Chrzanów and Bytom Synclines with the WNW–ESE-striking axes (Figs. 2, 3). Moreover, the faults and fault zones, distinguished in the Paleozoic basement, are not of the Variscan age exclusively, but they were in many cases rejuvenated in the Alpine tectonic epoch. The western part of the Upper Silesian Coal Basin was affected in the Variscan epoch by the fold tectonics, subordinated to the Moravian-Silesian (NNE–SSW) direction and eastern vergence.

In the final period of the Variscan cycle, granitoid plutonism developed in the Cracow–Myszków zone along the geosuture, with the related, locally occurring Cu-Mo-W porphyry deposits (C. Harańczyk, 1979; E. Górecka, 1993a; J. Żaba, 1995). Relatively large magmatic intrusion probably occurs in the vicinity of Olkusz at a great depth (R. Kucharski, 1996).

Lower Permian terrigenous sediments, locally associated with volcanic rocks: diabases, porphyries, melaphyres and their tuffs, are distributed along the named geosuture zone. The Lower Permian sediments filled a narrow, graben structure of general extension NW–SE (Fig. 2).

During the Upper Carboniferous and Permian times, erosion removed a significant part of the Paleozoic rocks from the Cracow–Myszków zone. Then, karst processes developed on the uneven surface of the Paleozoic platform.


Fig. 3. Zn-Pb deposits in the Chrzanów ore district (after M. Szuwarzyński, 1993)

*1* — Upper Paleozoic, *2* — extent of occurrence of the Mesozoic and Tertiary beds, *3* — axis of the Chrzanów syncline, *4* — fragment of the regional fault zone Trzebinia–Będzin, *5* — main zones of the transversal faults (arrows indicate the senses of the relative movements), *6* - exploited deposits of the Trzebionka mine, *7* — exhausted deposits, *8* — the area shown in Figure 6

Paleozoic beds are overlaid by Mesozoic sediments of the Silesian-Cracow Monocline, which is the common covering complex of the Upper Silesian Coal Basin and the Cracow–Myszków zone. Denudation of Variscides lasted till Röt (locally till Muschelkalk), when epicontinental sediments of a uniform facial development started to form in the whole Silesian-Cracow area. The sediments of the cover, mainly carbonates, are mostly of the Triassic and Jurassic age; the Cretaceous and Miocene sediments occur locally in grabens and in morphological depressions (Fig. 2).

The authors, who considered the structural evolution of the cover complex distinguish two tectonic cycles: Early Alpine (Cimmerian–Laramide) and Late Alpine (Tertiary). These cycles have different structural patterns.

The generally inclined to NE Silesian-Cracow Monocline, which started to form during the Late Cimmerian phase, obtained its present structure during the very intensive activity of the Laramide phase. After J. Krokowski (1984), in the pattern of the Early Alpine tectonic cycle the direction NW–SE to NNW–SSE was the meridional one of the regional importance, along which the right strike-slip movements occurred. The Laramide movements had most probably an essential influence on the joint fissure opening, and formation of the NW–SE and NE–SW as well as NNW–SSE and NNE–SSW fault systems.

A significant rearrangement of the Cimmerian–Laramide structures took place due to the Tertiary tectonic movements, connected with the formation of the Flysch Carpathians and their foredeep. At that time, tension and significant vertical mobility of the area played an important part. Dense fault network, striking meridionally and evenly to the parallel of latitude, resulted in blocky character of this area. The influence of the basement dislocations on the deformations of the overlying beds, and the propagation of the old disjunctive structures from the basement upwards, are commonly apparent. As a rule, the younger tectonic deformations rejuvenated and followed the directions of the older deformations. The dip-slip and oblique-slip faults prevail, frequently with associated flexural deformations. These faults form the presently-observed system of horsts and grabens. Geometric pattern and kinematics of the fault network was strictly connected with the polyphase activity of the large-scale dislocations in the deep basement (J. Żaba, 1995).

## TECTONIC CONTROLS OF THE ORE-FORMING PROCESSES

The main Zn-Pb deposits in the Silesian-Cracow region occur in the area between the towns of Bytom, Chrzanów, Olkusz and Zawiercie (Fig. 2). Two economically important mining regions are in this area: the Olkusz and Chrzanów ore districts. These ore districts will be the subjects of the further considerations. The rich Bytom deposits and the other ones, shown in the Figure 2, have been exhausted. Exploratory works have resulted in the discovery of several new Zn-Pb deposits in the Silesian-Cracow area, mainly in the Olkusz–Zawiercie zone.

The extent of ore mineralization in the vertical profile is related to the geologic structure (C. Harańczyk, 1979;

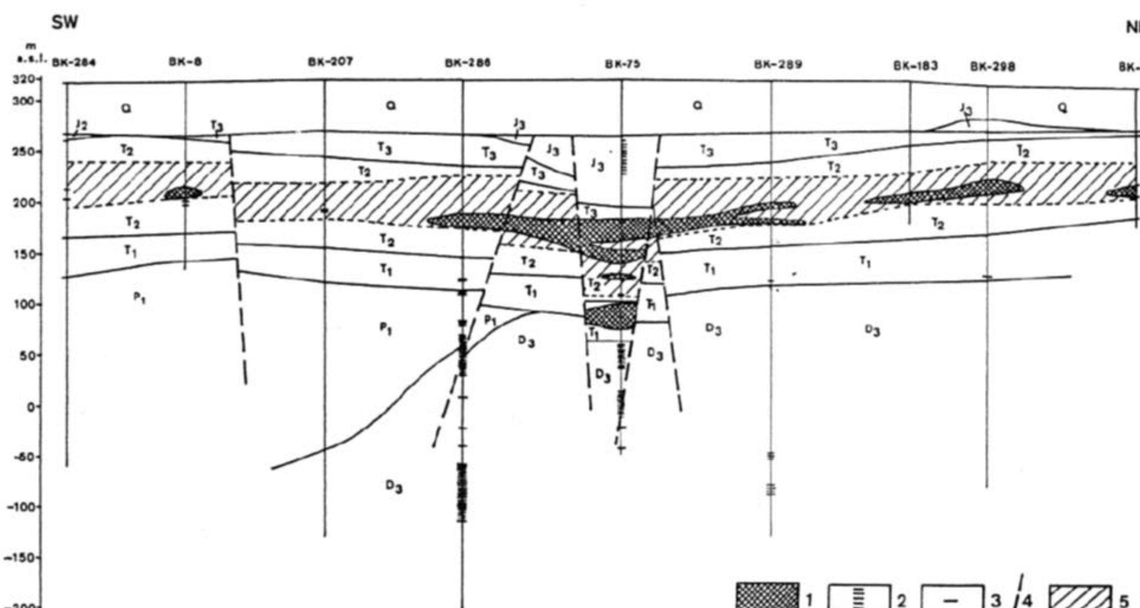



Fig. 4. Geologic cross-section of the Klucze Zn-Pb deposit in the Olkusz ore district (after E. Górecka, 1993b)

*1* — ore bodies, *2* — ore zones, *3* — ore veins, *4* — fault zones, *5* — extent of ore-bearing dolomites; $D_3$ — Upper Devonian, $P_1$ — Lower Permian, $T_1$ — Lower Triassic, $T_2$ — Middle Triassic, $T_3$ — Upper Triassic, $J_2$ — Middle Jurassic, $J_3$ — Upper Jurassic, Q — Quaternary

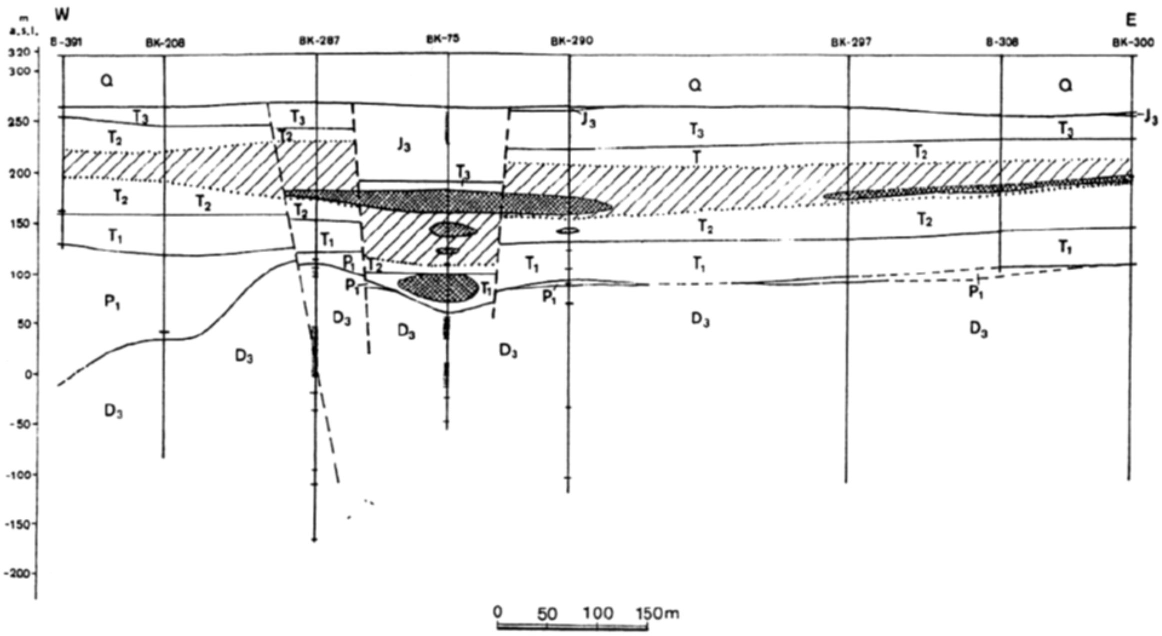



Fig. 5. Geologic cross-section of the Klucze Zn-Pb deposit in the Olkusz ore district (after E. Górecka, 1993b)

Explanations see Figure 4

M. Nieć, 1980; T. Gałkiewicz, 1983; R. Blajda *et al.*, 1992; E. Górecka, 1993a, b; M. Szuwarzyński, 1993). It is larger (from Devonian to Jurassic inclusively) in the areas, where the basement is built of pre-Triassic elevations of Devonian and Lower Carboniferous carbonate sediments, buried under the Mesozoic cover (Olkusz and Zawiercie districts), and smaller (mainly Lower Muschelkalk) at the places, where the basement of Triassic consists of Carboniferous and Permian clayey-sandstone and conglomerate sediments (Chrzanów and Bytom districts). The vertical extent of mineralization varies from several tens of centimetres up to several tens of metres. Locally, where the ores occur in the Paleozoic basement as well, the vertical extent of mineralization is even up to a few hundred metres, e.g. in the Olkusz district.

About 80 to 90% of the Zn-Pb ores are hosted by carbonate rocks of Lower Muschelkalk (lower Middle Triassic), mainly by so-called ore-bearing dolomites. Moreover, the Zn-Pb ores occur locally in Röt dolomites (uppermost Lower Triassic) and in the Middle to Upper Paleozoic carbonates, mostly of Devonian age. The Zn-Pb mineralization is rarely found in the Lower Paleozoic, Permian, Upper Muschelkalk and Jurassic sediments.

Although generally similar, nevertheless the individual ore regions are characterized by their tectonics, spatial distribution of the ore-bearing epigenetic dolomites, and ore mineralization, as well as by forms, structures and mineral composition of the ores (E. Górecka, 1996).

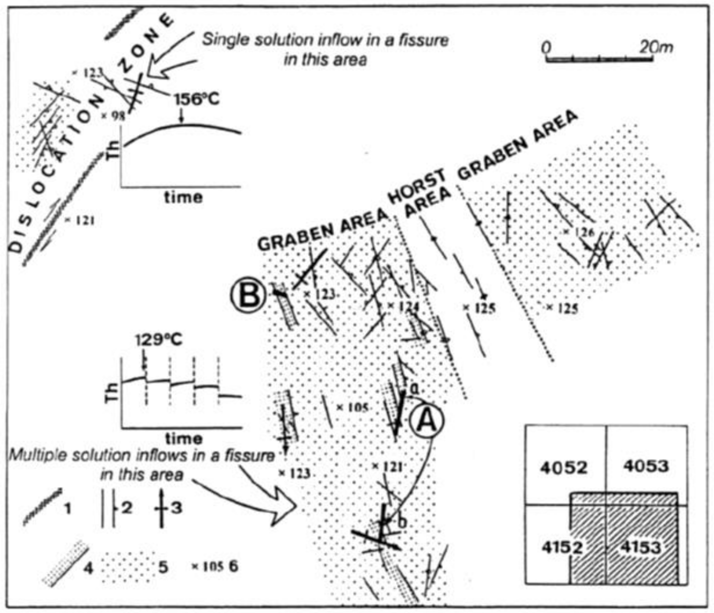
The forms of the ore bodies are very complicated. In the Mesozoic beds the deposits are tabular in shape. They consist of the disseminated, replacement- and cavity-filling-ores, the latter including crusted, veined, drusy and breccia varieties. Rich ore bodies are generally located in the lower part of the ore-bearing dolomites. The distribution of ore mineralization is controlled by joints. Ore bodies of this type have been better recognised in the mines, where they occur both in the Muschelkalk and Röt beds.

In the Upper Paleozoic carbonate sediments, the ore bodies are often located directly below the Triassic cover, sometimes building continuous ore bodies together with the ores from the Triassic cover (Figs. 4, 5). Several small- and middle-sized ore bodies have been explored in the Olkusz–Zawiercie–Siewierz area. These ore "nests" are usually distinguished by limited horizontal and relatively large vertical extents. The ore bodies are commonly associated with faults.

The extension of the Zn-Pb ore bodies was influenced directly by tectonics and by karst processes. The various metasomatic and karst ore-forming processes in Muschel-

Fig. 6. Tectonic map of a part of the Trzebionka mine, and Zn-Pb mineralization within the Lower Muschelkalk beds, thermal regime of ore precipitation from Th values of fluid inclusions given; the numbers of the exploitation parcels in the main map area are shown in the hatched rectangle

*1* — regional fault (arrows indicate the senses of the relative movements), *2* — small faults, often with slickensides, and large vertical and inclined fractures, *3* — anticlines and flexures, *4* — zones of intensive development of ore breccias (the heavy lines A and B mark the positions of the profiles shown in Figs. 7 and 8), *5* — areas of the ore mineralization occurrence, *6* — elevation points, in metres a.s.l.




kalk carbonate rocks in the Silesian-Cracow district have been presented in numerous publications (S. Dżułyński, M. Sass-Gustkiewicz, 1985, 1993; M. Sass-Gustkiewicz, 1985; D. L. Leach *et al.*, 1996b). The studies of mutual relations between tectonic effects and Zn-Pb mineralization in the Paleozoic and Mesozoic beds, performed recently, are an important contribution to understanding the origin of the Silesian-Cracow deposits.

Tectonic-mesostructural studies performed in the underground workings of the Trzebionka mine near Chrzanów revealed, that the tectonic factor was most important for the deposit development and concentration


Fig. 7. Profile of the wall of the Trzebionka mine gallery

*1* — bedding traces of ore-bearing dolomites, *2* — fractures, at places ore-mineralized, *3* — ore-mineralized caverns, *4* — ore-mineralized breccias and cataclasis, *5* — crushed material of the ores (W. Jaroszewski, 1993; S. Kibitlewski, 1993). Figures 6–8 present a part of the investigation area; the studies were made in the carbonate rocks of the Lower Muschelkalk age. In regional sense this area is a part of the inter-fault block, bordered by dislocation zones of higher range (regional dip-slip and strike-slip faults; Fig. 3). One of the dislocation zones, which is more than ten metres wide and strikes NE–SW, is in the western part of the area. In addition to small-scale folds, assemblages of slickenside structures and steep faults are typical in this zone. Thin encrustations of ores occur on the surfaces of these faults and slickensides (E. Górecka, 1996). This evidences the direct influence of the compression tectonics on the process of ore formation.

The area of the inter-fault block is internally disturbed by structures of lower range like bucklings, widely-spaced folds, minor faults (normal and reverse), slickensides, flexures, joints, fractures, and resulting structures — horst and graben areas. Horizontal strike-slip movements along the bedding traces, connected locally with brecciation, were also found.

The disjunctive structures are ore-mineralized in various degree. Relatively large ore concentrations were found in fissures, developed in the fields of tectonic stress, generating local folds, minor faults and slickenside structures, what indicates the ore mineralization development under conditions of tectonic activity, i.e. from forced, not free flow of mineralizing fluids. Moreover, the fractures accompanying the bending of the beds and horizontal strike-slip movements are more frequently filled with ores than joints and inter-bed fissures. Joints in the undisturbed beds are usually barren.

Ore mineralized zones of the dolomite breccias associate steep or vertical faults and major fractures of the NNW–SSE strike. The bedded ore breccias, developed along surfaces of the dolomite layers are also present. The breccias display various degrees of dolomite disintegration, from cataclastic crushing of the layers without their visible deformation to typical breccias with complete destroying of the bedding. Many of them, especially the bedded breccias, are probably of the pressure-hydraulic origin (W. Jaroszewski, 1993). As a rule, the contacts of the ores with the host rock are sharp. Distinct paths for fluid flows in form of the karst broadening of fissures and inter-layed rifts were not found.

The observed variation of the ore formation intensity, as relater to the character of the tectonic structures implies the conclusion, that the ores concentrated mainly in the downthrown parts of the disjunctive and related structures (faults and flexures), and less in the crests of the anticlinal structures. Development of all these structures was probably connected with the network of the ledge faults, which was active in the basement (S. Kibitlewski, 1993). The downthrown sides of such faults, as the zones of fissure formation and crushing, could be the places of favourable conditions for concentration of large amounts of ores.

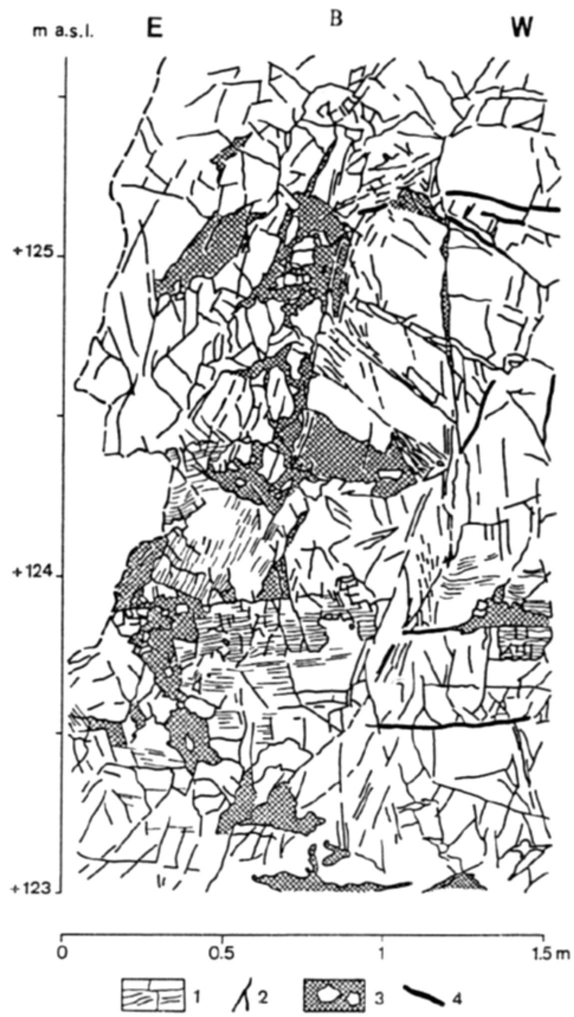



Fig. 8. Profile of the wall of the Trzebionka mine gallery

*1* — dolomites with locally discernible lamination, *2* — bedding traces and main fractures at places ore-mineralized, *3* — ore-mineralized tectonic breccias, *4* — ore veins

The tectonic phenomena, as an important factor of the Zn-Pb deposit formation, were also found in the Olkusz ore district. The performed studies yielded the data for determination of mutual relations between the tectonic activity effects and ore mineralization in the Paleozoic and Mesozoic beds (C. Harańczyk *et al.*, 1971; R. Blajda *et al.*, 1992; E. Górecka, 1993b; Figs. 4, 5). A connection was stated between the intensity of the ore mineralization pro-

The ore bodies, frequently forming lenses arranged in "beds", associate the systems of the normal and reverse faults, which are the components of large fault zones of regional importance. Ores occur as well in tectonic breccias, developed along the Variscan faults (E. P. Slowey *et al.*, 1995).

The problem of the tectonic control of the Zn-Pb ores has been discussed with respect to the Mississippi Valley-type deposits as well (A. V. Heyl, 1972, 1983; C. W. Clendenin *et al.*, 1989; C. W. Clendenin, M. J. Duane, 1990; K. B. Horrall, 1995). It was indicated, that these deposits are located along the lineaments, transecting the American continent. One pointed to the metallogenic importance of the deep-seated and repeatedly reactivated faults, including the strike-slip faults, which were the conduits, leading ore-forming fluids from depth.

## MIGRATION OF HYDROTHERMAL FLUIDS

Any consideration of the zinc and lead sulfide ores origin in the Silesian-Cracow area the features, discussed above in the present paper and that ones, presented by A. Kozłowski (1995), and A. Kozłowski *et al.* (1996). The presence of vertical thermal gradient evidences a vertical migration of the solutions, whereas an upward increase of temperature ranges points to the ascension of these solutions with their cooling near the Earth's surface. The solutions were not local, at least not all were local formation brines, because of the temperature difference between solutions and wall rocks found commonly in the vertical extent of ore mineralization. On the basis of analysis of the vertical ore zoning at Klucze, C. Harańczyk (1963) and E. Górecka (1993b) also evidenced the ascending type of ore-forming solutions.

The present-day thermal regime of the area of interest is not known satisfactorily, however, the data published by several authors (J. Kowalczuk, J. Pałys, 1967; K. Chmura, 1975; J. Majorowicz, 1977) gave a general outline of temperatures and heat flow. Temperature variation versus depth, determined in boreholes, yielded rock (and formation waters) cooling of 2.8 to 5°C per 100 m of vertical extent. The highest temperature was measured in the borehole Goczałkowice IG 1 (S part of the Upper Silesian Coal Basin) at depth of 2950 m for Devonian aquifer as equal 100.5°C (A. Różkowski, A. Różkowska,

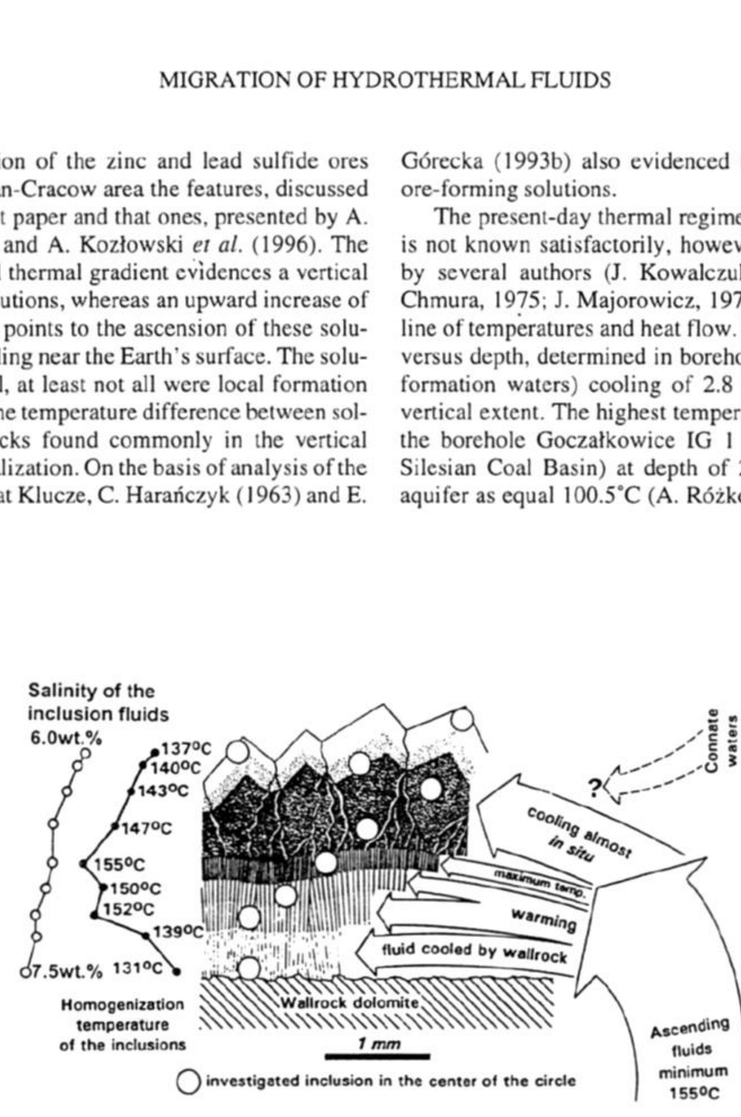



Fig. 10. Banded fibrous and granular sphalerite (sample from Trzebionka mine; dislocation zone in Fig.6) with fluid inclusions, whose homogenization temperatures showed parent fluid cooling, caused by wallrock, then gradual warming and finally again cooling. Temperature regime and very small variation of salinity of the inclusion fluids together with sphalerite habits strongly suggest a single inflow of fluid in the fissure, with subsequent cooling in almost stagnant conditions. Slight decrease of salinity in inclusions from wallrock to outer granular sphalerite may indicate limited mixing of connate or meteoric waters with ascending fluids (after A. Kozłowski, 1995)

cess and the extension of the fissure development as well as the position of the studied area within the large tectonic units.

Variation of the faulting intensity, causing the development of the graben and horst structures, one may connect with extensive systems of the faults of the strikes close to NNE–SSW, NNW–SSE and WNW–ESE. In addition to the dominating dip-slip and oblique-slip faults, the reverse faults occur in the Olkusz ore district. The right strike-slip and reverse faults are the components of large tectonic zones, coincident with the regional direction of the NW–SE geosuture zone.

Large ore bodies occur in tectonically depressed areas of the graben type, that appeared due to movements along deep-seated block faults of ledge (vertical dip-slip) character. Post-Jurassic age of these structures, formed by strike-slip faults, determines also age of the ore bodies as Cretaceous–Tertiary. The Late Alpine age of the Zn-Pb mineralization in the Silesian-Cracow area is also indicated by paleomagnetic studies (D. T. A. Symons *et al.*, 1995).

In some pits of the Olkusz mines of the Zn-Pb ores one performed the structural analysis of the deposits on the basis of the fracture tectonics of the Triassic beds (J. Górecki, 1977; S. Kibitlewski, E. Górecka, 1988; J. Cabała, 1995; Fig. 9). The relation was indicated between certain assemblages of tectonic fractures, which preceded the development of the fissure and breccia-type ore deposits. Mineralization of various fracture assemblages may be connected with their periodical activity as tensional systems; this activity might have occurred separately for individual systems or jointly under conditions of multiple relaxation. Probably the pre-existing and open or opening fractures displayed an important part in formation of caverns and karst brecciation as factors, stimulating these processes (cf. also C. Harańczyk, 1988).

Thus, the accepted scheme of the formation of the Zn-Pb deposits in the Chrzanów and Olkusz ore districts implies the conclusion, that the tectonic structures caused migration of the ore-forming fluids from depth. The faults, stemming from the Paleozoic basement, were the conduits of the ore-forming fluids flow; afterwards fluids percolated the Mesozoic cover. The easy vertical propagation of the strike-slip faults and their large amplitudes caused a significant extent of the faults at depth (R. Dadlez, W. Jaroszewski, 1994). This feature caused the metallogenic importance of the strike-slip faults. However, majority of the worldwide known ore deposits of the fault type is not located directly in the fault fissure, but in its neighbourhood, most frequently in the fissured rocks adjoining the fault (*op. cit.*). Probably, fluid flow caused by pulsations of the environment volume, so-called seismic pumping (R. H. Sibson *et al.*, 1975) is an important factor of the mineral-forming activity of the strike-slip faults.

The above-characterised strike-slip geosuture zone of deep extent displayed for a long time an important metallogenic role in the Silesian-Cracow area. A polyphase, pulsating development of the Zn-Pb ores is apparently connected with this suture; the ore deposits occur on both sides of the geosuture zone (Figs. 1, 2). The mobile Carpathian belt could generally stimulate the tectonic phenomena, influencing the migration process of the fluids, independently of the type of the mineralizing solution reservoir.

The connection of the formation of the Zn-Pb deposits with tectonic processes have been described for many other deposits included to the carbonate-hosted type.

The Irish Zn-Pb deposits occurring in Lower Carboniferous in the areas of Irish Midlands (deposits Silvermines, Galmoy and Lisheen) and Dublin Basin (deposits Navan, Ballinalack and Keel) may be a good example. Hydrothermal origin and connection with the compression-tensional tectonic movements are accepted for these deposits formed in the Variscan cycle (M. W. Hitzman, 1995; J. D. Johnston, 1995; P. Redmont, 1995; E. P. Slowey *et al.*, 1995).

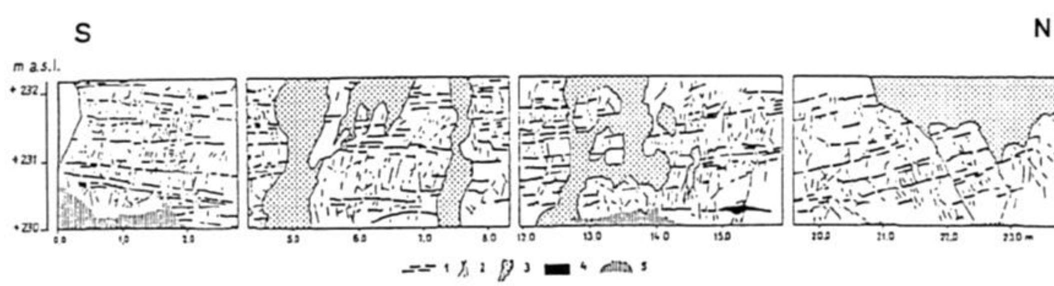



Fig. 9. Vertical chimney-like dolomite ore breccias in the gallery wall profile, Pomorzany mine (after S. Kibitlewski, E. Górecka, 1988)

*1* — bedding traces of ore-bearing dolomites, *2* — fractures, *3* — dolomite-ore breccias, *4* — cavern, *5* — crushed material

1973). Generally, the western part of the area has higher temperatures than the eastern one. To some extent it is consistent with maximum temperatures of ore formation yielded by fluid inclusions in sphalerite, which were distinctly higher in the south-west area (maximum 156°C) than in the north-east one (maximum 138°C). However, both rock temperature and geothermal gradient of the rocks are lower than these of ore-forming solutions, which were equal 6 to 10°C. If there was no a distinct difference in thermic regime of the country rocks at the time of ores deposition, when compared with the present-day conditions, the quick cooling of ore-forming fluids, as found by inclusion studies, and appearance of ZnS supersaturation in the solutions were reasonable.

The ore-forming solution flow was tectonically controlled at least at the early stages of ore mineralization (E. Górecka, 1996). It appears from the presence of fissures filled by solution either in a single event with later cooling (Figs. 6, 10), or during several events with distinct change of solution type in each event, associated with crushing of the growing sphalerite crystals (Fig. 11). The solution type changes resulted in its varying temperature, salinity and sodium/calcium ratio (A. Kozłowski, 1995).

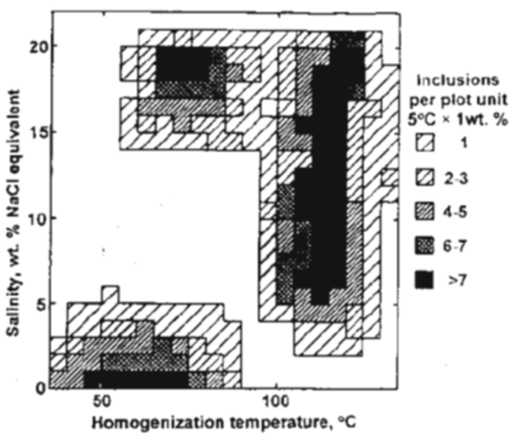



Fig. 12. Salinities and homogenization temperatures of 836 fluid inclusions in sphalerite from Klucze ore field, and Olkusz, Bolesław, Pomorzany and Trzebionka mines. The results split into three fields, characterized by moderate to high salinity and high temperatures (ascending fluids), high salinity and moderate temperatures (probably formation waters), and low salinity and low to moderate temperatures (apparently meteoric waters). Ascending fluids probably were influenced by the two latter types of waters

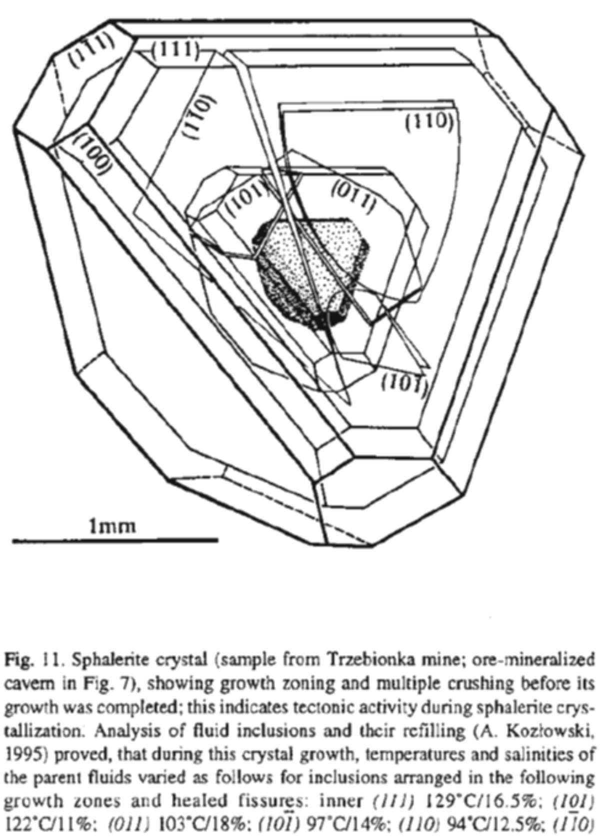



Fig. 11. Sphalerite crystal (sample from Trzebionka mine; ore-mineralized cavern in Fig. 7), showing growth zoning and multiple crushing before its growth was completed; this indicates tectonic activity during sphalerite crystallization. Analysis of fluid inclusions and their refilling (A. Kozłowski, 1995) proved, that during this crystal growth, temperatures and salinities of the parent fluids varied as follows for inclusions arranged in the following growth zones and healed fissures: inner *(111)* 129°C/16.5%; *(101)* 122°C/11%; *(011)* 103°C/18%; $(10\bar{1})$ 97°C/14%; *(110)* 94°C/12.5%; $(1\bar{1}0)$ 88°C/16%; outer *(111)* 88°C/16%. The present authors explain this sequence of changes as multiple inflows of various solutions

The three groups of fluids found (A. Kozłowski *et al.*, 1996), characterized by low salinity/high temperature, high salinity/moderate temperature and very low salinity/low temperature most probably should be attributed to ascending solutions, formation brines and meteoric waters, respectively (Fig. 12). Ascending solutions of unknown origin mixed first with saline formation waters. Hypsometrically higher, the second mixing with dilute meteoric waters caused not only a sharp decrease of salinity but also a temperature drop. The mixing mechanism is responsible in part for distinct variations of temperature, salinity and composition of ore-forming solutions. The performed fluid inclusion studies did not submit any indication of possible separate sources of metals and sulfur, and sulfide precipitation on mixing, thus this problem will not be discussed here. An extensive discussion of the possible sulfide ion sources based on the sulfur isotope data is presented by D. L. Leach *et al.* (1996a), and lead isotope studies by S. E. Church *et al.* (1996) made suggestions on the source of lead.

C. Harańczyk (1993), on the basis of isotope studies, presented a two-source solution model, that may mean at least two sources; he also attempted the determination of ores precipitation temperatures by mode of sulfur isotope partition between sphalerite and galena from the ores disseminated in dolomite and in their massive variety, receiving the temperatures of about 300°C. However, R. O. Rye (1974) observed a very large variation for sulfur isotope fractionations in natural coeval sphalerite-galena pairs, formed at the temperature range 200 to 110°C. He explained this feature by sulfur isotope disequilibrium, that may occur in the low-temperature hydrothermal deposition. The homogenization temperatures, determined for the Silesian-Cracow sphalerite, are almost exactly in this range, thus an independent check of sulfur isotope equilibria is necessary. Meanwhile, the dendritic, fibrous and colloform sphalerite and galena habits would indicate rather disequilibrium conditions during many mineralization events in the studied ores. The stalactite forms of sphalerite, present in the Silesian-Cracow deposits and interpreted as karstic speleothem, might have resulted from rapid crystal growth under hydrothermal conditions due to mixing of an acidic and an alkaline solution (I. K. Anderson *et al.*, 1995), i.e. disequilibrium crystallization. It is woth noting, that temperatures, estimated on the basis of the CAI values for the Silesian-Cracow area (J. E. Repetski, M. Narkiewicz, 1996) are consistent with the fluid inclusion temperature data.

Studies of the recent saline waters sampled at various depths in the ranges: from Earth's surface to 3000 m below it, and located in the Silesian-Cracow region, distinctly showed gradual salinity decrease from about 20 weight percent at the largest depth to nearly nil at the surface (A. Różkowski *et al.*, 1979 — Fig. 5) . This is an evidence of the transition: brine–meteoric waters, still existing in the area under study, probably due to mixing of the two components. Fossil evidences were found in results of metasomatic dedolomitization processes, that developed in environment of mixed meteoric and hot waters (K. Mochnacka, M. Sass-Gustkiewicz, 1978). The third, ascending component has not been evidenced neither by the latter authors, nor by A. Różkowski *et al.* (1979), however, the salinity changes, recorded by these authors, fit well to the upper part of the salinity profile found in fluid inclusions. Moreover, A. Różkowski *et al.* (1979 — Fig. 6) gave the main ion characteristics of the brines as rich in sodium in Devonian and Carboniferous rocks, and sodic-calcic to calcic in Devonian and Triassic ones, a distinct two-fold spectrum of compositions like that one found in the studied fluid inclusions in sphalerite.

Changes of the sodium and calcium contents in parent fluids of the ores resulted not only from mixing process, but also from solution/wallrock interaction. Wallrocks were almost inexhaustible source of calcium (and magnesium). During percolation through the wallrocks, solutions should dissolve calcite and dolomite, that resulted in increase of Ca and possibly Mg contents in waters. This differentiation have been found in inclusions in minerals of the investigated ores. The area of the Chrzanów ore district yielded calcium-poor compositions of fluids, whereas to the north, in the Olkusz ore district, the calcium-rich fluids are very common. This feature strongly suggests the solution migration from south to north (A. Kozłowski, 1995), especially if considered jointly with higher maximum temperatures and smaller short-time salinity variations in the southern area than in the northern one.

The solution/wallrock interaction might have resulted in incorporation of organic matter (hydrocarbons) from limestone or dolomite to ore-forming solutions by any mode presented earlier in this report. Chloroform leachates from Middle Triassic dolomites or limestones without ore mineralization (A. Kozłowski, 1995) evidenced the presence of organic matter very similar to that determined in ore minerals. Moreover, thermovacuum decrepitation analysis (V. A. Alekseenko *et al.*, 1978) yielded gas emission from ore-bearing dolomite samples at temperature above 400–450° C, due to decomposition of disseminated organic matter present in the rocks. The oxygen-bearing hydrocarbon compounds (ether or carbonyl molecules and acetate ion) leached from ore minerals indicated, that the organic matter consumed oxygen, yielding its low fugacity, i.e. maintaining reducing conditions. This resulted in the occurrence of sulfide sulfur in ore-forming solutions. Probably ammonia found in ore-forming solutions (J. G. Viets *et al.*, 1996) was also of organic origin. Thus, this component, whose presence caused alkalization of solution, apparently was introduced to ore-forming fluids from wallrocks.

Detailed tectonic studies, summarized earlier in this paper, evidenced tectonically-controlled, high-pressure flow of ore-forming fluids that resulted not only in ore precipitation, but also in the wallrock crushing and disintegration. These hydrotectonic phenomena are believed to be of Alpine age. Hence, the suggestion is reasonable, that the rejuvenation of older brittle deformations and their extension to younger rocks plus mobilization of fluids in a regional scale, were due to the Cretaceous/Tertiary (Alpine) orogenic event, that occurred to the south of the present-day ore region. That event was the formation and uplift of the Carpathian mountainous chain with its northward-oriented overthrust of a series of nappes on pre-Tertiary and partly Tertiary basement. Stress of the nappes mass have had to change the hydrostatic equilibria in the aquifers, when the rocks were plunged and new migration paths for waters (tectonic zones) were opened. The present authors avoid the discussion, whether the fluids were formation waters, or waters released from hydrous minerals by increasing pressure and temperature. The pressurized fluids should be pushed to the north of the overthrusting nappes, i.e. toward the northern margin of the just-forming Carpathian Foredeep and southern slope of the Variscan platform and its post-Variscan cover. The similarity of ages of these phenomena and Zn-Pb mineralization, as well as the characterized features of the mineral-forming fluids, concluded from fluid inclusion studies, make the supposition reliable, that the regional flow of fluids, generated by the folding of the Carpathians, was an important, or maybe, even basic factor, causing the origin of the discussed ore deposits. Similar features were found in

North American Mississippi Valley-type (MVT) deposits, confirming a tectonic link between the Appalachian–Ouachita orogeny and the MVT Zn-Pb ores formation of the Ozarks (C. W. Clendenin, M. J. Duane, 1990; C. W. Clendenin *et al.*, 1994).

The waters, mobilized by the overthrusting Carpathians, might be the ascending solutions, identified by means of fluid inclusion studies in sphalerite. They could achieve increased temperature from inner Earth's heat inflow, which in the zone between the Carpathians and the Góry Świętokrzyskie Mts. is almost highest in Central Europe, between 1.6 and 2.0 $\mu cal/cm^2 \cdot s$ (R. Hohl, 1977). This narrow high-heat-inflow zone, extending in front of the Carpathians, may indicate a deep discontinuity in the Earth's crust.

The source of sodium chloride in the formation brines, participating in the ore origin, could not be located in Miocene evaporites of the Carpathian Foredeep, because the latter are too young. Probably, the marine basin of the future salinary sedimentation was formed as morphologically variable trough (A. Radwański, 1968, 1969) at the time of either ores precipitation, or its decline. Proposal of the brine flow from the Upper Silesian parallic-limnic coal basin (A. Różkowski *et al.*, 1979), if not supported with evidences, is not necessary, because Triassic sediments in the area of ores formation bear evaporite intercalations.

The source of metals for the deposits of the type similar to the Silesian-Cracow ones, is located commonly in rocks that were the objects of the fluids percolation on their way to the discharge area. The suggestions for the Silesian-Cracow ores made till now were based on lead isotope analyses in insufficient number of the samples (R. E. Zartman *et al.*, 1979, S. E. Church *et al.*, 1996), thus they may be evaluated only as preliminary.

## RELATION OF THE SILESIAN-CRACOW ORE DISTRICT TO OTHER CARBONATE-HOSTED Zn-Pb DEPOSITS

Carbonate-hosted Zn-Pb deposits are included to the Mississippi-Valley type (MVT) by a prominent group of investigators throughout the world. Such classification suggests their genetic relations to the respective North-American deposits. Extensive studies of the Silesian-Cracow ore deposits, and the analysis of the world literature of the subject, frequently revealed important differences in geological structures, forms of occurrence as well as in mineral and chemical compositions of the ores, when compared to other deposits, included to the MVT, e.g. to the Zn-Pb deposits in the USA.

Analysis of the Polish and foreign publications proved, that in many cases the genesis of individual Zn-Pb deposits was estimated on the basis of the studies of only certain features and concentration processes, e. g. the karst ones, with omitting other factors, e.g. lithostratigraphic and tectonic. This makes difficult or impossible to perform the complex comparative analysis of various Zn-Pb deposits and their reliable genetic classification.

Apparently, in the present-day state of the Zn-Pb deposit studies, including the MVT, the extensive investigations of fluid inclusions in ore and barren minerals may yield the basis of a comparative analysis, as it was shown for the Polish and American deposits (A. Kozłowski, 1995; A. Kozłowski *et al.*, 1996; D. L. Leach *et al.*, 1996c; J. G. Viets *et al.*, 1996). The main features and problems, resulting from the analysis of the published data, are as follows:

1. Homogenization temperatures for MVT deposits are given in ranges 75–200 or 50–220°C (E. Roedder, 1967, 1968, 1971, 1977; J. T. Chesley *et al.*, 1994). This agrees well with the Th values of the Silesian-Cracow ores, ranging from 80 to 158°C.

2. Vertical thermal gradient of 6 to 10°C, found at the Silesian-Cracow deposits, is "unusual for MVT deposits and has been documented only in North America at the Nanisivik mine in Canada" (D. L. Leach, J. G. Viets, 1992).

3. Regional horizontal homogenization temperature change, higher values in the south, lower in the north of the ore-mineralized area in the Silesian-Cracow region. Horizontal thermal gradients were suggested for the Illinois–Kentucky fluorspar district (C. D. Taylor *et al.*, 1992), next discarded as a small-size local fluctuation near the cryptovolcanic Hicks Dome complex (P. G. Spry, G. D. Fuhrmann, 1994). The figure, presented by D. L. Leach (1993 — Fig. 3, p. 114), suggests lateral thermal gradient of 0.1°C per km for sphalerite from four principal MVT districts in the Ozark region versus the distance from the Ouachita foldbelt: However, the used Th values are modes and a mean, thus the values to which any natural importance can barely be bound.

4. Continuous presence of Na and Ca ions in fluid inclusions in MVT ores and variable Na/Ca ratios in inclusions in the Silesian-Cracow ores.

5. Inclusion fluids in the MVT ores yielded total salinity 10–30 weight percent, whereas the Silesian-Cracow ones from nul to about 23 weight percent, what means distinctly lower values for the latter.

6. The MVT deposits have signs of activity of high-salinity connate waters (sometimes of two kinds) and low-salinity meteoric-water dominated fluids, mixed at various stages of minerals precipitation (P. G. Spry, G. D. Fuhrmann, 1994). However, mineral precipitation occurred frequently without parent fluid mixing (J. T. Chesley *et al.*, 1994). The Silesian-Cracow ores formed from fluid being a mixture of three components, two of them of low salinity and each of the two of different nature.

7. Both types of the ore deposits formed in the presence of liquid organic matter, though their types are different for each of them.

The above discussion indicates, that despite certain similarities, the including Silesian-Cracow deposits to the MVT is premature, because differences are great and genetically significant; the problem requires further studies, for instance in geochemistry of trace elements in ores and host rocks (H. Qing, E. W. Mountjoy, 1994). The present authors appreciate the importance of the tectonic processes for formation of the carbonate-hosted Zn-Pb deposits, and the necessity of such studies for construction of the deposit models, e.g. of the geometric or genetic types. These models may be prepared both for individual ore bodies and for whole deposits or ore districts. The correctly constructed models may display an important role in further theoretical studies and practical activity in geological survey.

*Translated by Andrzej Kozłowski*

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# ŚLĄSKO-KRAKOWSKIE ZŁOŻA Zn-Pb : ROZWAŻANIA O PROCESACH ZŁOŻOTWÓRCZYCH

(z 12 fig.)

*Słowa kluczowe*: Polska, obszar śląsko-krakowski, siarczki Zn-Pb, złoża w skałach węglanowych, typ Mississippi Valley, uwarunkowania tektoniczne, migracja fluidów, inkluzje fluidalne, procesy złożotwórcze.

## STRESZCZENIE

Omówiono położenie śląsko-krakowskich złóż Zn-Pb na tle budowy strukturalnej obszaru (fig. 1–3). Wykazano związek okruszcowania z tektoniką dysjunktywną (fig. 4–9). Szczególne nasilenie mineralizacji kruszcowej stwierdzono w towarzystwie rowów tektonicznych, generowanych przez uskoki regionalne o charakterze przesuwczym. Pojurajski wiek tych struktur tektonicznych określa zarazem wiek złożowej koncentracji kruszców na kredę i trzeciorzęd. Dynamika procesów tektonicznych (kompresyjnych i tensyjnych) oddziaływała na przepływ roztworów zmineralizowanych i koncentracje kruszców. Analiza struktur tektonicznych dowodzi istnienia wpływu sieci uskoków rozwiniętych w głębszym podłożu) na rozwój złóż Zn-Pb.

Na podstawie wyników badań inkluzji fluidalnych w sfalerycie przedyskutowano możliwe sposoby migracji roztworów macierzystych kruszców. Wykazano, że w zależności od sytuacji tektonicznej kruszce powstawały z roztworów, które wypełniały szczeliny w trakcie jednokrotnego dopływu lub też wielokrotnych, pulsacyjnych dopływów roztworów o zmiennej temperaturze i koncentracji soli (fig. 10–11). Kruszce powstawały w środowisku, które utworzyło się w wyniku mieszania trzech fluidów: roztworów ascensyjnych, wód formacyjnych i wód meteorycznych (fig. 12). Przeprowadzone badania, wraz z analizą porównawczą, wykazały, że zaliczanie wszystkich złóż Zn-b występujących w skałach węglanowych, w tym złóż śląsko-krakowskich, dotypu Mississippi Valley jest dyskusyjne.