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FLUID INCLUSION STUDY OF CARBONATE-DOMINATED VEINLETS FROM COAL SEAMS AND ROCKS OF THE CENTRAL AND WEST BOHEMIAN BASINS, CZECH REPUBLIC

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ABSTRACT
Fluid inclusions in carbonate-dominated veinlets from selected Czech Upper Paleozoic basins display large variations in salinity (0–25 wt. % eq. $NaCl/CaCl_2$) and smaller variations in the homogenization temperatures (41–112 °C). We suggest that the trapped fluids represent a mixture dominated by heated formation fluids.

KEYWORDS: fluid inclusions, Carboniferous, bituminous coal, Plzeň Basin, Kladno-Rakovník Basin

1. INTRODUCTION

Fluid inclusion analysis represents a standard technique for the estimation of the mineral and/or fluid temperatures (e.g. Roedder, 1984; Samson et al., 2003). However, they have rarely been used in the study of coal-bearing basins, where thermal modeling is mostly based on the reflectance of organic matter, on the temperatures of Rock-Eval pyrolisis, or on analysis of bio-markers. Fluid inclusions were successfully employed in the study of the temperature evolution of the South Wales coal basin (Alderton et al., 2004), for example.

This study is concerned, via fluid inclusion data, with discussion of the nature, temperature evolution and timing of various carbonate, barite and quartz veinlets from several coal basins in central and western Bohemia. Nature of these veinlets is unknown, theoretically they might formed during maximum burial, or shortly after it (i.e. diagenetic origin from formation fluids), or they may have formed later from (tectonically?) expulsed basinal fluids (i.e. late diagenetic origin from (heated?) formation fluids), or they (or some of them) may be related to thermally driven fluid circulation in the vicinity of an obscured intrusive volcanic centre (i.e. hydrothermal origin).

Upper Paleozoic basins in central, western and north-eastern Bohemia (Fig. 1) are filled exclusively with continental clastic sediments. The only exception is the Upper Silesian Basin of mixed origin, where parallic as well as continental sediments can be found. Fluvial sediments dominate over lacustrine sediments in all these basins. Lacustrine sediments and weakly coalified sediments locally contain horizons of tuffs/tuffites. Dikes and sills of acid volcanites can occasionally be found. Carbonate, barite or quartz veinlets occur locally, however without apparently marked regional distribution. Larger veins seem to be associated with the vicinity of local brittle faults; however, this phenomenon was rarely documented.

Ore and gangue minerals from the Central and Western Bohemian basins were extensively studied during the early mining boom (e.g. Feistmantel, 1856; Bořický, 1864; Ježek, 1913; Slavík, 1925, 1947; Kratochvíl, 1932 and Kašpar, 1939). These studies focused mostly on description of the mineral forms and on paragenetic relationships. They distinguished: 1) mineralization within coal seams; 2) mineralization in 'pelosiderite' concretions (incipient diagenetic stage); and 3) mineralization associated with fractures and breccia zones in the surrounding rocks. The generalized succession scheme according to Kašpar (1939) is (from oldest to youngest): older carbonates (siderite, ankerite, dolomite), barite, sulphides, whewellite, nacrite, young carbonates (calcite) and secondary minerals (sulphates). In contrast to historical papers, more recent studies mostly focus only on secondary minerals, either of natural or of anthropogenic origins (formed recently in burning coal tips; e.g. Žáček, 1989, 1998; Sejkora et al., 2000).

At the Kladno-Rakovník Basin (Fig. 1), carbonate and barite veins/veinlets or individual crystals of barite and whewellite are associated with narrow dislocation fractures in the vicinity of major

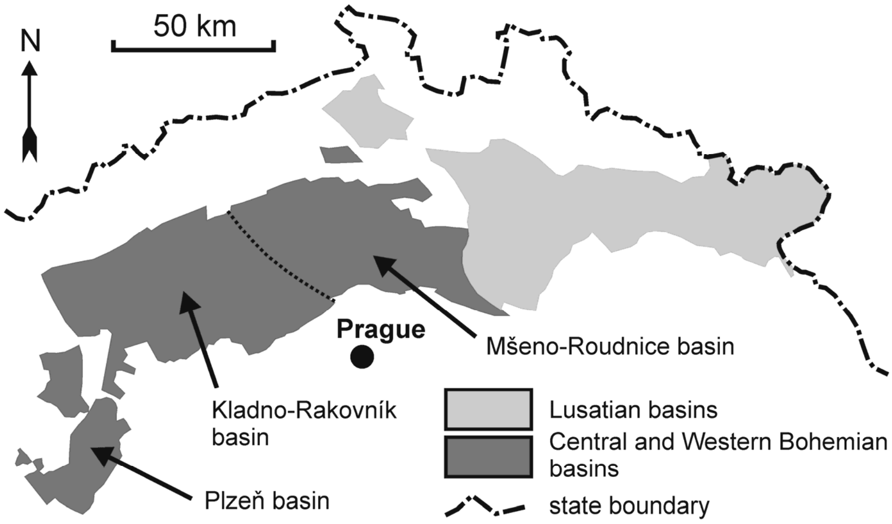

Fig. 1 Scheme map of Central and Western Bohemian and Lusatian basins.

faults. Veinlets/fractures do not represent widespread phenomena, but locally yielded large, well-formed crystals of barite and whewellite.

At the Plzeň Basin (Fig. 1), carbonate and barite veins/veinlets were documented in seven boreholes in the vicinity of the villages of Chotíkov and Malesice (to the W and NW of Plzeň). The veinlets are 5–7 mm thick and occur in a zone 2–3 km wide and trending NW-SE (Pešek, 1972). The veinlets were found in psammites and in claystones or siltstones of the Kladno, Týnec and Slaný formations and also in the Neoproterozoic basement (shales).

This paper presents the first microthermometric data on fluid inclusions trapped in various carbonate, barite or quartz veinlets that crosscut coal seams and the surrounding Carboniferous sediments in central and western Bohemia. All the samples, except one, are associated with local faults or fractures that crosscut coal seams and possibly thus postdate the burial maximum. The second author collected all the samples during the 1960's to 1990's, either in originally active mines (Kladno-Rakovník Basin) or from coal-exploration drilling cores (Plzeň Basin), or at pit tips (one sample only; Intra-Sudetic Basin). Stratigraphically, the samples correspond to depths of ~100 m to ~900 m below the present surface (Fig. 2). The thickness of the Carboniferous sediments in the Plzeň Basin, especially at its margins, was probably less than in the Kladno-Rakovník Basin. However, no apparent difference in the vitrinite reflectance (thermal evolution) between these two basins was noticed.

2. METHODS

Samples were collected underground in active mines, or from exploration drill cores. From an original collection of more than 20 samples, we have selected the 10 most promising samples for study of the fluid inclusions using double polished wafers about 200 to 100 μm thick. In order to prevent thermal damage to the fluid inclusions during preparation of the wafers, they were fixed to a glass plate by acetone-soluble, cyanoacrylate glue.

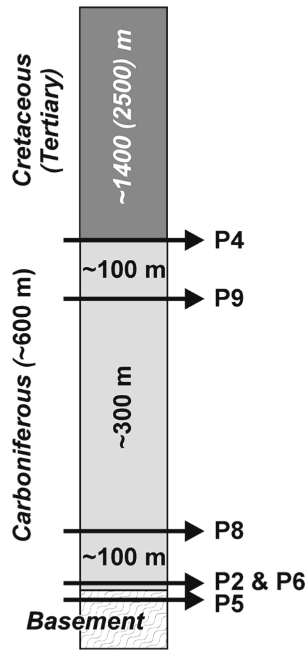

Fig. 2 Schematic stratigraphy of Upper Paleozoic coal basins in central and western Bohemia. Arrows indicate approximate position of the studied samples.

Careful microscopic study (sample textures, mineral and fluid inclusion identification) was performed using a Leica DMPL polarizing microscope (magnification up to 1000x). Fluid inclusion microthermometry was carried out using an Olympus BX-40 microscope (magnification up to 800x) and THMSG 600 Linkam heating-freezing stage. The degree of fill (F) of the fluid inclusions is expressed as the liquid to liquid plus vapor volumetric ratio. The measured temperatures (in °C) include: T_{fm} (temperature of first melting), T_{mh} (temperature of melting of the salt hydrate), $T_{m\text{-}ice}$ (temperature of melting of the last ice crystal), Th_{tot} (total homogenization temperature). The salinity is expressed as wt. % eq. NaCl, using the relationship of Bodnar (1993). T_{fm} and T_{mh} were measurable typically in only a few inclusions. $T_{m\text{-}ice}$ was measured more frequently, however, not in every studied inclusion. Th_{tot} was usually readily visible, even in very small inclusions, or in poorly transparent samples.

3. SAMPLES STUDIED

The fluid inclusions were studied in 7 samples of mostly carbonate veinlets hosted by various coal seams (3 samples), or by Carboniferous clastic sediments (3 samples) and also by metamorphosed rocks of the Neoproterozoic crystalline basement (1 sample). The veins are oriented more or less (± 30°) perpendicularly to the preserved sedimentary bedding and often exhibit tension textures (incipient sigmoidal form). The only exception is sample P4, where the veinlet is parallel to the bedding. Two samples (P2, P15) showed visible coal alteration (manifested by loss of coal brightness) within the zone with veinlets. A description of the samples follows:

3.1. KLADNO-RAKOVNÍK BASIN

Sample P2a: Kladno-Rakovník Basin, Radnice Member, Upper Radnice coal seam, Bolsovian, 600 m below the surface, sample size 20 x 10 x 5 cm. Sheeted stringer of thin (up to 3 mm) to hair-like veinlets in coal (Fig. 3a). The veinlets are filled with grayish ankerite and with kaolinite (possibly younger than ankerite). Some veinlets form en-echelon or horse-tail arrays. The veinlets are more or less perpendicular (± 5°) to the coal bedding.

Sample P2b: Kladno-Rakovník Basin, Radnice Member, Upper Radnice coal seam, Bolsovian, 600 m below the surface, sample size 3 x 4 x 3 cm. Carbonate-barite vein (8–20 mm thick) in coal (Fig. 3c). The vein is filled with massive white calcite (up to 20 mm thick) and with a narrow zone of subhedral crystals of barite (only 2 mm thick; Fig. 3d). Calcite is younger than barite. Because of the limited sample size, the relationship of the vein to the coal bedding is ambiguous (possibly inclined at 70°).

Sample P4: Kladno-Rakovník Basin, Kounov Member, claystone, Stephanian B, drill-core Dch-1, 445.2 m, core diameter 9 cm, sample height 3 cm. Alternation of light-grey and dark-grey claystone. Beige dolomite forms an irregularly shaped veinlet parallel to the bedding. The veinlet contains numerous drusy vugs (Fig. 3b).

Sample P15: Kladno-Rakovník Basin, Radnice Member, Upper Radnice coal seam, Bolsovian, 600 m below the present surface, sample size (12 x 8 x 6 cm), massive quartz-carbonate veinlet about 3-10 mm thick in the plane of a small normal fault (Fig. 3e).

PLZEŇ BASIN

Sample P5: Plzeň Basin, Neoproterozoic shale, core Co-21, 652.9 m, diameter 9 cm, sample height 10 cm. Dark grey graphite-bearing shale, weakly foliated with weak pyrite impregnation. An about 8 mm thick veinlet crosscuts the metamorphic foliation and is inclined at about 30° to the drill-axis. The veinlet is dominated by greyish quartz. Drusy vugs are locally present and incompletely filled in with younger beige dolomite.

Sample P6: Plzeň Basin, Radnice Member, arkosic sandstone, Bolsovian, core Co-17, 554.6 m, diameter 9 cm, sample height 6 cm. Coarse-grained arkose sandstone. Massive beige dolomite forms a steeply inclined vein (deviation about 15° from the drill-axis, thickness 1–10 mm). The vein morphology resembles a tension gash.

Sample P9: Plzeň Basin, Malesice Member, claystone, Stephanian B, core Co-12, 180 m, sample size 15 x 10 x 4 cm. Two sub-parallel veins (10 and 25 mm thick) of white to pinkish coarse-grained carbonate in light-grey pelite. One vein contains numerous drusy vugs with rare crystals of younger pyrite. The vein is approximately perpendicular to the preserved sedimentary bedding.

4. FLUID INCLUSIONS

Four types of aqueous-only fluid inclusions were identified: 1) monophase liquid (type L); 2) monophase vapor (type V); 3) two-phase liquid-rich (type Lr; Figs. 3f and 3h); and 4) two-phase vapor-rich (type Vr). No daughter or trapped solids were found in the studied inclusions.

Carbonates host large numbers of small and poorly transparent fluid inclusions (< 5 μm in size) arranged along growth zones, or in the form of a three-dimensional cluster in the core of a carbonate crystal. In some cases, an inclusion-free growth zone(s) rims the cluster (Fig. 3g) and confirms thus primary nature of enclosed inclusions. Type L or V inclusions predominate, type Lr, or Vr inclusions occur isolated or in clusters and are significantly less frequent. Inclusions in barite are similar to those in carbonates, except for their greater size (up to 20 μm) and mostly secondary origin (see below). Microthermometric data are summarized in Figures 4–6 and in Table 1.

4.1. KLADNO-RAKOVNÍK BASIN

Samples P2a and P2b: Fluid inclusions in barite occur in trails (often parallel with fractures in the younger calcite), or form clusters. They are mostly of secondary origin. Type L inclusions are

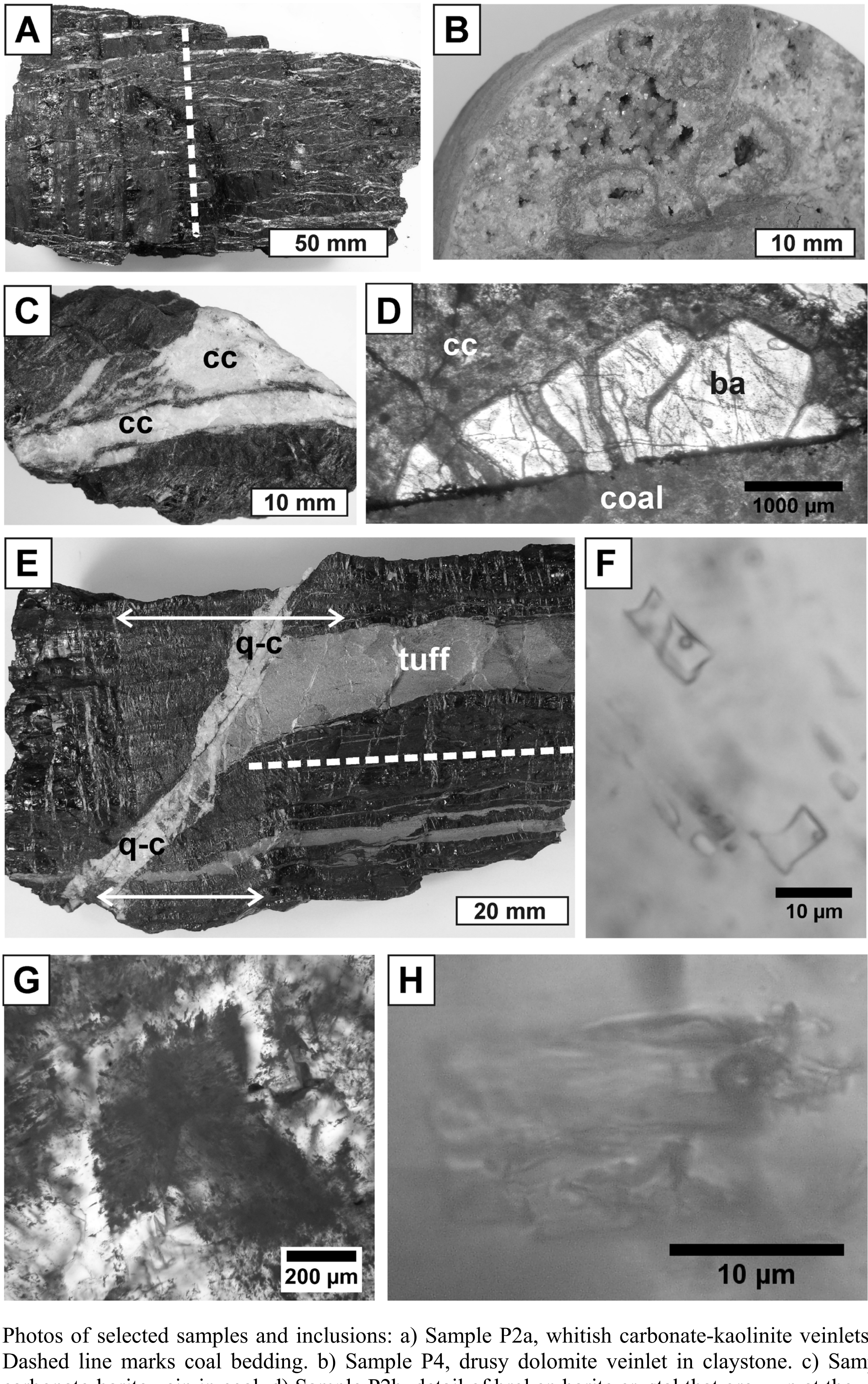

Fig. 3 Photos of selected samples and inclusions: a) Sample P2a, whitish carbonate-kaolinite veinlets in coal. Dashed line marks coal bedding. b) Sample P4, drusy dolomite veinlet in claystone. c) Sample P2b, carbonate-barite vein in coal. d) Sample P2b, detail of broken barite crystal that grew up at the wall-rock of fractured coal. Carbonate overgrows barite and fills in fractures in broken barite. e) Sample P15, quartz-carbonate (q-c) veinlet filling in plane of normal fault in coal. Solid arrowed lines mark extent of coal alteration manifested by lowering of reflectance. Dashed line highlights coal bedding. f) Two-phase liquid-rich fluid inclusion (type Lr) from sample P8. g) Sample P4, carbonate rhombohedra with a fluid inclusion-rich core and with an inclusion-free rim. h) Two-phase liquid-rich fluid inclusion (type Lr) hosted by carbonate of sample P4.

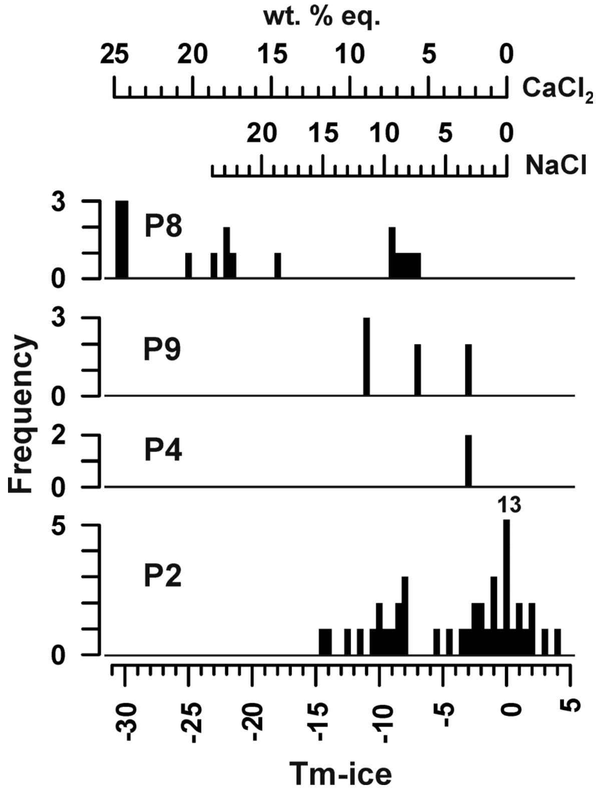

Fig. 4 Summary histogram of temperatures of melting of last ice crystal ($T_{m\text{-}ice}$) and estimated fluid salinities (eq. NaCl or eq. $CaCl_2$).

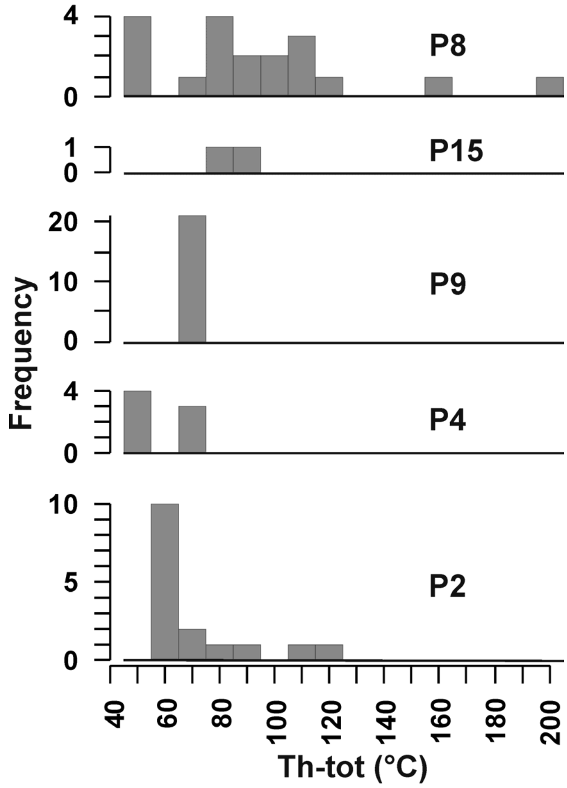

Fig. 5 Summary histogram of total homogenization temperatures (Th_{tot}) of type Lr inclusions.

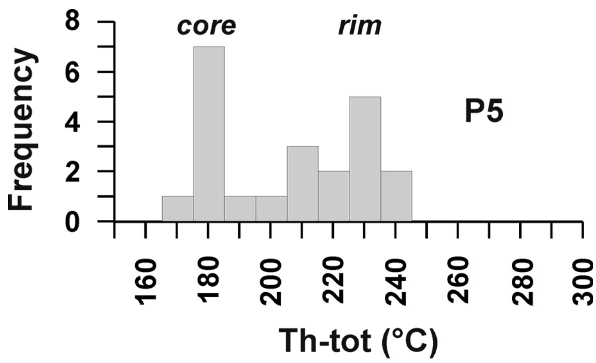

Fig. 6 Histogram of total homogenization temperatures (Th_{tot}) of type Lr inclusions from a veinlet (sample P5) hosted by Neoproterozoic shale from the Plzeň Basin basement.

oval, 5–20 μm in size and predominate. Type Lr (F: 0.95–0.60) occurs together with type L, however, is relatively scarce. A single trail (type Lr; S5 assemblage in Table 1; homogeneous F: 0.95), located close to the rim of a barite crystal, constitutes an exception to this rule. These inclusions homogenized (Th_{tot}) within a very narrow range from 51 to 57 °C (10 inclusions; 3 inclusions homogenized from 61.3 to 81.9 °C). T_{fm} in both types (L, Lr) occurred from -33 to -30.6 °C, and $T_{m\text{-}ice}$ varied significantly, from +4 to -14.5 °C. Temperatures of $T_{m\text{-}ice}$ > 0 °C suggest metastable melting. Metastable melting behaviour of type L inclusions is further evident from the poorly reproducible $T_{m\text{-}ice}$ data. The estimated salinity varies significantly from 0 to 18 wt. % eq. NaCl. No correlation between $T_{m\text{-}ice}$, Th_{tot} and the spatial distribution of the individual inclusions in the samples was identified. In total, seven inclusion assemblages (labeled S1 trough S7; Table 1) were measured.

Sample P4: Type L and V inclusions (5–30 μm large) predominate (Figs. 3g-h); type Lr (F: 0.95–0.85) represents no more than 10 % of all inclusions. T_{fm} (-48 °C) and $T_{m\text{-}ice}$ (-3 °C) were measured with difficulty, due to the poor sample transparency. Th_{tot} was measured in all the studied inclusions (41–70 °C); most data are clustered between 41 and 50 °C.

Sample P15: Inclusions (Lr type) in carbonate are small (< 10 μm), relatively scarce and have similar degrees of fill (F: 0.90–0.95). Two inclusions homogenized to the liquid state at 89.5 and at 92.8 °C (Th_{tot}). $T_{m\text{-}ice}$ was poorly identifiable, around -11 °C (in one inclusion only), corresponding to a salinity of about 15 wt. % eq. NaCl.

Table 1 Summary of microthermometric data.

Sample	Assemblage	Fill (F)	Mineral	T_{fm} (°C)	T_{mh} (°C)	$T_{m\text{-}ice}$ (°C)	Salinity (wt. % eq.NaCl)	Th_{tot}[1] (°C)	n[2]	Th_{tot}[3] (°C)	n[2]
P2	S1	1.0	barite	(-26)		+ 1.8 to -5.6 (12)	0.2 – 8.7				
	S2	0.90-1.0	barite	-33		- 8.3 to -9.5 (10)	12.0 – 14.5	109 – 111.6	2		
		0.90				- 0.8 to -3.6 (4)	1.4 – 5.9	78	1		
	S3	1	barite			-11.9 to -14.5 (3)	15.9 – 18.2				
	S4	1	barite			- 0.1 to -0.4 (5)	0.2 – 0.7				
	S5	0.95	barite	-32		+ 4.0 to -1.6 (7)	0.2 – 2.7	51.2 – 61.3	11	55.8 ± 4.1	11
								78.0 – 111.6	3		
	S6	0.95	barite	-31		0 to - 0.3 (3)	0.0 – 0.5				
	S7	1.0	barite			- 2 to -3 (4)	3.4 – 5.0				
P4	P-PS	0.95	quartz	-48		-3 (2)	5	41 – 50	4	45.3 ± 4.0	4
								65 – 70	3	66.7 ± 2.5	3
P9	P	0.95	calcite	-52	-39 to -36	- 7 to -11.1 (5)	10.5 – 15.0	64 – 70	21	67.4 ± 1.9	21
P15	P	0.95	calcite	-45 ?	-	?	?	80.5 – 92.8	2	91.0 ± 2.0	
P8	P-PS (ass. 1)	0.95-1.0	quartz	-52 to -56	-40 ?	-7.4 to -9.2 (6)	11.0 – 13.1	45 – 49; 107	3	(47 ± 2)	2
								67 – 89	5	75.2 ± 8.4	5
	PS (ass. 2)	0.95	quartz	-62		-30.1 to -30.9 (6)	28.7 – 29.2	86 – 115	6	96.3 ± 10.5	6
	S (ass. 3)	0.95-0.8	quartz	-49	-40 ?	-18.3 to -25.2 (6)	21.2 – 25.7	71 – 111.5	7	94.2 ± 13.5	7
				-62 ?				>150	3		
P5	P	0.90	quartz	?	?	- 3 to -4 (4)		166.1- 236	22	201 ± 25	22

Notes: [1]total range (all data); [2]number of data; [3]average and standard deviation of representative data ;

4.2. PLZEŇ BASIN

Sample P5: Quartz veinlet filled with drusy quartz. Late carbonate fills in drusy vugs in the quartz. Inclusions (Lr type) in quartz are small (< 10 μm) and have homogeneous degree of fill (F: 0.90–0.95). Inclusions in the carbonate were not studied because of their poor transparency. Two assemblages were studied in the quartz: i) inclusions in a growth zone close to the outer rim of the quartz crystal; and ii) inclusions in the quartz crystal representing several successive growth zones, from core to rim. Inclusions homogenized to the liquid state from 166 to 236 °C (Th_{tot}; Fig. 6). The quartz crystal exhibited a gradual increase in Th_{tot} from the core (~180 °C) towards the rim (~230 °C). $T_{m\text{-}ice}$ was poorly identifiable at -4 to -3 °C (n=5).

Sample P8: Up to 20 mm large crystals of milky to transparent quartz with several growth zones. Fluid inclusions commonly exhibit a sculpted surface and are dark, poorly transparent and monophase (vapor?). Rarely, two-phase, vapor-rich (Vr; F: 0.2–0.4), liquid-rich (Lr; F: 0.9) or monophase liquid (L; F: 1) inclusions were identified. Some inclusions formed parallel arrays (trails), where the inclusion long axes were oriented perpendicularly to the growth zone.

Three assemblages were measured: 1) a 3D-cluster of monophase (type L) inclusions with one extraordinarily large (70 x 25 μm), two-phase inclusion (Lr; F: 0.90) and with a trail of pseudosecondary (?) two-phase inclusions (Lr), all located close to the core (base) of a quartz crystal; 2) fan-like 2D-cluster of elongated Lr (F: 0.95; with sparse type L) highly saline inclusions (28.7–29.2 wt. % eq. NaCl) arranged symmetrically with respect to the quartz c-axis; and 3) two trails of secondary flat-shaped inclusions (21.2–25.7 wt. % eq. NaCl); one trail contained mostly Lr inclusions (F: 0.95) while the other was dominated by L inclusions.

Sample P9: Subhedral to euhedral grains of milky carbonate with several growth zones highlighted by alternation of inclusion-rich (dark) and inclusion-poor (transparent) zones. Inclusions in transparent zones are small, immeasurable and probably filled with vapor. Inclusions in dark zones are 3 to 150 μm in size and two-phase (Lr; F: 0.95; about 30 % of all inclusions), with monophase liquid (L; about 40 %) or monophase vapor (V; about 30 %). All these inclusions can be classified as primary. T_{fm} in Lr inclusions occurred from -52 to -56 °C, T_{mh} from -39 to -36 °C (in several inclusions only) and $T_{m\text{-}ice}$ at -11.0 to -11.2 °C (except two inclusions that melted repeatedly at -7 to -7.2 °C). Inclusions (Lr) homogenized from 64 to 70 °C to liquid (21 data, Th_{tot}). Two inclusions, possibly stretched, homogenized above 100 °C.

5. DISCUSSION

5.1. BURIAL EVOLUTION OF CENTRAL BOHEMIAN CARBONIFEROUS BASINS

The burial evolution of the Central and Western Bohemian Carboniferous basins has not been extensively studied. The only model that is available was developed by Holub et al. (1997) for the Mšeno-Roudnice Basin (Fig. 1). According to this model, sediments in this basin reached a maximum thickness of ~2,000 m at ~260 Ma (Permian), followed by rapid erosion to about 600 m during the Triasic and followed by renewed burial to about 2,000 m at ~86 Ma. Maximum burial temperatures are estimated to reach ~100 °C during both the Permian and the Tertiary. The model suggests erosion of about 1,400 m of sediments during Permian/Triasic times. Similar models for other Central and Western Bohemian basins are absent, and only subjective estimates suggest the absence of about 2,000 m of sediments in the present profile.

An early phase of diagenetic evolution of the Kladno-Rakovník basin can be deduced from the oxygen and carbon isotope data of Carboniferous pelosiderite concretions (Žák and Skála, 1993) from the Kladno-Dubí area. The carbon isotope composition of these concretions evolves from highly positive values ($\delta^{13}C_{siderite}$ = 11 ‰ PDB; core) to negative ones ($\delta^{13}C_{siderite}$ = -7 ‰ PDB; rim). This trend indicates initiation of concretion growth from CO_2 produced by bacterial oxidation of organic matter, possibly only a few meters below the sediment/water interface. However, the central and peripheral zones of the concretion formed from CO_2 generated by abiogenic thermal decomposition of organic matter at greater depths (< ~500 m). The oxygen isotope composition of siderite varies less significantly. A decrease of only about 1 ‰ was observed from the core ($\delta^{18}O_{siderite}$ = 22.0 to 22.1 ‰ SMOW) to rim ($\delta^{18}O_{siderite}$ = 21.2 to 20.8 ‰ SMOW). Suggesting constant oxygen isotope composition of the fluid, the observed trend implies an increase in temperature of only about 5 °C during formation of the studied concretion (i.e. from its core to the rim). The concretions most probably formed at temperatures lower than 50 °C.

5.2. COMPOSITION OF TRAPPED FLUIDS

Progressive burial or low-T metamorphism of sediments rich in organic matter first generates fluids dominated by higher hydrocarbons, later fluids dominated by CO_2 and/or CH_4 and then, at temperatures above ~200 °C, aqueous fluids (e.g. Mullis et al., 1994). The burial evolution of coal-bearing sediments from South Wales resulted in a similar sequence: water and CO_2 during early burial, then petroleum-rich fluids and finally, at >150 °C, CH_4-dominated fluids (Alderton et al., 2004).

In our study, the presence of only aqueous fluids may indicate either an incipient burial stage or a late burial stage (after the burial maximum, at > 200 °C), or a hydrothermal input independent of burial evolution.

All the samples (except P6) are associated with normal faults that dislocated already-mature coal seams. The carbonate veinlets thus most probably postdate the maximum burial. The salinity of the trapped aqueous fluid varies significantly from almost 0 wt. % eq. NaCl to more than 24 wt. % eq. $NaCl/CaCl_2$ (Table 1, Fig. 4). First melting (T_{fm}) temperatures as low as -48 to -62 °C suggest the fluids should be modeled in the H_2O–$CaCl_2$±NaCl system for samples P4 and P9. When coupled with high to medium salinity, the fluids may be considered to be evolved basinal fluids (sample P9). On the other hand, low-salinity fluids (< 5 wt. %) in other samples may indicate infiltration of modified groundwater of meteoric origin or of a metamorphic fluid from the basement. There is no apparent correlation in the salinity between the studied samples and their location in the individual basins.

5.3. *COMMENTS ON THE OCCURRENCE OF INDIVIDUAL INCLUSION TYPES*

The studied fluid inclusion assemblages typically contain more than one inclusion type: monophase liquid (L) inclusions are the most frequent in some samples, while monophase vapor inclusions (V) are more common in some others. Two-phase inclusions (Lr, Vr) were usually sparse. The common occurrence of all these inclusion types suggests the occurrence of necking down on sample cooling (Bodnar et al., 1985).

The trapping temperatures of monophase inclusions (L) may vary theoretically from ~120–150 °C down to near ambient temperatures. Due to the metastable absence of a vapor phase in monophase inclusions, we must rely on the homogenization temperatures of sparse two-phase Lr inclusions to estimate the fluid temperature. Unfortunately, Lr inclusions may be affected by post-entrapment modification (stretching or partial leakage), especially in fragile minerals like carbonates or barite (as here). Therefore, fluid inclusion assemblages with more than three Lr inclusions were preferentially measured. When the measured Th_{tot} data were similar, then the assemblage was considered to be unstretched/unleaked. An alternative approach to elimination of the probable effect of post-entrapment changes is to use only the lowest measured Th_{tot} data from each sample for final interpretation (i.e. data with higher Th_{tot} are suspected to be affected by partial leakage).

5.4. *VEINLETS FROM THE KLADNO-RAKOVNÍK BASIN*

All the studied veinlets crosscut sedimentary bedding of Carboniferous strata or the coal seams. They could have formed during the late diagenetic stage, or even after maximum burial. Homogenization temperatures (Th_{tot}) of two-phase (Lr) inclusions vary from 41 to 112 °C (to the liquid state; Table 1, Fig. 5). When data are plotted with respect to their suggested stratigraphic position (Fig. 7a), an increase in Th_{tot} values with increasing depth can be distinguished. In addition to this general trend, the data exhibit two slightly different temperature intervals for each stratigraphic level.

There are several ways of interpreting the total homogenization temperatures of aqueous inclusions from sedimentary basins: 1) inclusions trapped in syndiagenetic, fragile minerals, like the carbonate matrix of the sediment, tend to continuously re-equilibrate on progressive burial to adapt to increasing temperatures. The measured Th_{tot} data are then interpreted as the maximum temperatures that the sample experienced (e.g. Barker and Goldstein, 1990); 2) inclusions trapped in minerals that can sustain some degree of over/under pressure (e.g. quartz) do not re-equilibrate on progressive burial and thus require application of a pressure correction in order to transform the homogenization temperature into the true trapping temperature (i.e. true fluid temperature); 3) A special case occurs when inclusions are trapped from a heterogeneous fluid. Then the homogenization temperatures of unmixed fluid end-members approach the true fluid temperatures (e.g. Alderton et al., 2004); 4) In addition to the above-mentioned options, interpretation of the data may be hindered by the occurrence of necking down or of other post-entrapment processes.

Based on inclusion petrography, we can exclude heterogeneous trapping (case 3). Inclusion shapes and morphology do not show visible post-entrapment modification also (case 4). The major factor in interpreting of Th_{tot} data is thus actual value of fluid pressure during mineral growth.

Figure 7a suggests Th_{tot} data to be more or less equal to the true fluid temperature. This could happen for continuous re-equilibration (case 1) or for severe basinal compartmentation into hydrodynamically isolated cells, where the fluid pressure is much lower than would correspond to a fully hydrostatic load. The lowest Th_{tot} data for each sample/depth result in a minimum estimate of the geothermal gradient of about 25 °C/km. A higher value (40 °C/km) is obtained if the upper range of Th_{tot} data is used. For comparison, Holub et al. (1997) suggest a gradient of about 50–55 °C/km for the maximum burial conditions. This hypothetic interpretation would account for the diagenetic nature of fluids and for formation temperatures not exceeding the maximum burial temperatures. Based on the presence of specific Al-organic complexes preserved in coal matter from the Czech part of the Upper Silesian Basin, Straka and Náhunková (2009) suggest that these coals did not experienced temperatures higher than 85–95 °C. Direct application of this temperature to the evolution

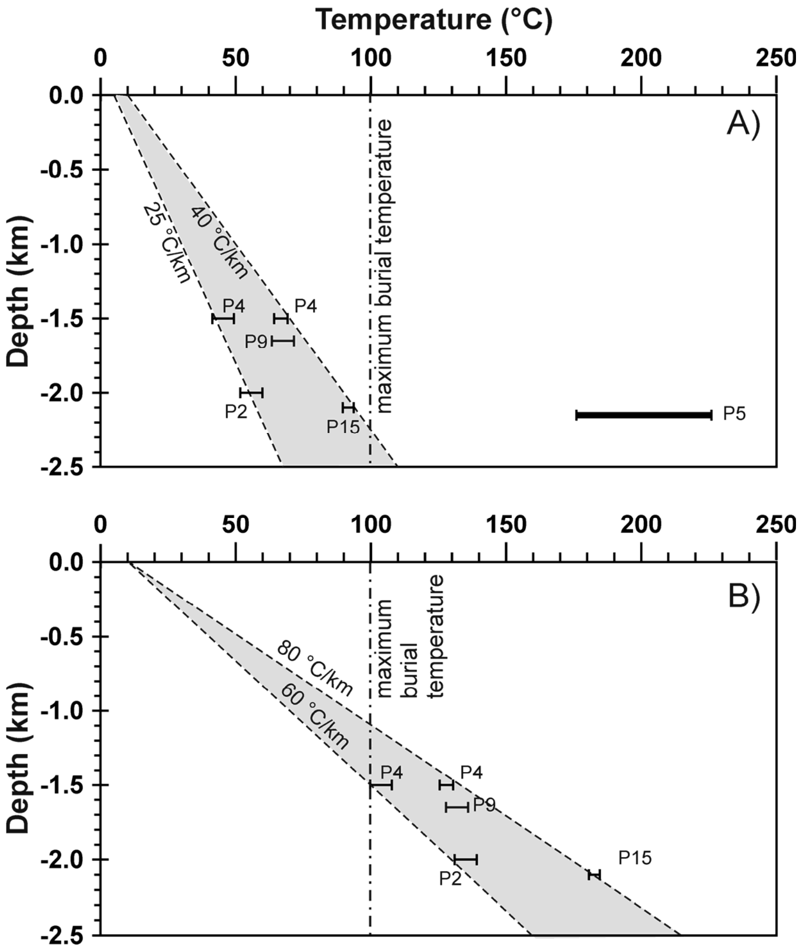

Fig. 7 Two hypothetical interpretations of depth-temperature relationships: a) based on measured Th_{tot} data, i.e. no pressure correction (P_{fluid} = inclusion homogenization pressure); b) based on Th_{tot} data corrected for depth (P_{fluid} = hydrostatic pressure load).

of Central and Western Bohemian coal basins is problematic, due to the different geological setting of the Upper Silesian Basin.

Figure 7b suggests much higher fluid pressure than Figure 7a. The fluid pressure in sedimentary basins down to depths of about 2 km tends to be hydrostatic, while it converges to lithostatic conditions below 3–5 km. In our case (≤ 2 km of sediment thickness), the fluid pressure should reflect the hydrostatic load. The homogenization temperatures (55 and 93 °C) for samples near the base of Carboniferous strata corrected for their respective maximum burial depth (Fig. 2) result in trapping/fluid temperatures of 156 and 187 °C, respectively. These temperatures are about 60–90 °C higher than the maximum burial temperature (~100 °C) proposed by Holub et al. (1997). This model would impaly a hydrothermal nature of the mineralizing fluids. The absence of any known intrusive/volcanic centre, a likely source of heat for extensive hydrothermal circulation, however, seems to contradict this hypothesis.

Many studied samples come from the immediate vicinity of faults (normal faults). The fault zones might serve as conduits for fluids across two or more stratigraphic horizons. Then the fluid pressure would be higher than the minimal value (Fig. 7a), but possibly still well below the value of a fully hydrostatic load (Fig. 7b). A paleogeothermal gradient of about 35–45 °C/km and fluid temperatures of about 10–20 °C higher than the measured Th_{tot} data thus represent a reasonable estimate of the formation conditions of the studied veins. The veins probably originated from heated formation fluids; limited mixing with a hydrothermal fluid (of meteoric origin?) is possible, especially due to large variations in the fluid salinities. Finally, a limited thermal (and chemical?) disequilibrium between the fluids and the surrounding coal seams can be suggested, based on the occurrence of a chase in the coal-reflectance in a zone up to 5 cm wide along the contact with the carbonate veinlets.

5.5. VEINLETS FROM THE WESTERN MARGIN OF THE PLZEŇ BASIN

Pešek (1972) noted the apparently frequent occurrence of carbonate ± barite veinlets in Carboniferous strata from a NW-SE trending zone, about 2–3 km wide, in the vicinity of the villages of Chotíkov and Malesice. He suggested that these veinlets might record hydrothermal and tectonic activity independent of burial evolution.

Our fluid inclusion data indicate a marked dissimilarity between quartz-carbonate veinlets from the Neoproterozoic basement (sample P5) and those occurring within the Carboniferous strata (sample P12). The most striking difference is much higher homogenization temperatures of primary fluid inclusions (~200 °C) in the sample from the Neoproterozoic shale, coupled with a marked gradual increase in Th_{tot} from the core to the rim of this quartz crystal (Fig. 6). Veinlets from the Neoproterozic basement therefore represent an older hydrothermal event, not related to the evolution of veinlets found in the Carboniferous strata.

6. CONCLUSIONS

Carboniferous strata from several coal basins in Central Bohemia contain carbonate, quartz-carbonate or barite veinlets that crosscut the strata at high angles. These minerals contain numerous primary, aqueous fluid inclusions which are mostly monophase (liquid or vapor) but rarely two-phase (liquid-rich and vapor-rich).

Extensive variability in the salinity (0–25 wt. % eq. $NaCl/CaCl_2$) of the trapped fluids, as well as the inferred value of the geothermal gradient (~40 °C/km) point to the predominance of heated formation waters. The homogenization temperatures of two-phase liquid-rich inclusions with homogenous liquid-to-vapor ratios range from 41 to 93 °C, where most of the data are clustered between 50 and 80 °C. These temperatures represent the theoretical minimum fluid temperatures. The actual fluid temperatures were, however, probably higher by about 10 to 20 °C because of pressure corrections.

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