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New constraints on the Middle Palaeozoic to Cenozoic burial and thermal history of the Holy Cross Mts. (Central Poland): results from numerical modelling

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ABSTRACT

A 1-D burial-thermal modelling was performed using data from two borehole sections representative of the central part of the Holy Cross Mts. area. This area is located in the axial part of the Permian-Mesozoic Mid-Polish Trough that was inverted during the latest Cretaceous-Paleocene. The modelling involved different variants of restored stratigraphy of eroded Carboniferous to Cretaceous strata, whereas calibration was based on samples from cored Middle-Upper Devonian sediments. The modelling results are consistent with the assumption of a Variscan (Carboniferous-Early Permian) heat flow elevated up to 80 mWm^{-2}, which is further confirmed by independent regional evidence. The zone of increased thermal maturity in the Devonian may be partly accounted for by a thicker Carboniferous section (by ca. 500 m) compared to previous estimates. Two variants of the post-Carboniferous geohistory were analysed. The variant of a thinner Permian-Mesozoic section, implying lower magnitude of the Late Cretaceous-Paleogene inversion, allows more realistic assumptions regarding heat flow distribution through time, including the possibility to incorporate an elevated Variscan heat flow. The alternative scenario, assuming deeper burial, generally lower heat flow and smaller Carboniferous thickness, is regarded as less probable. The accepted variant of the Permian-Mesozoic burial history implies that the total post-Carboniferous burial in the study area was on the order of 2000-2500 metres rather than 3000-3500 metres. The respective Upper Cretaceous thickness could have been 400 to 500 m instead of ca. 1000 m, whereas the Late Cretaceous-Paleogene inversion more likely started in the Santonian than in the late Maastrichtian. Consequently, the preferred magnitude of total inversion was on the order of 2500 m.

KEYWORDS | **Basin modelling. Subsidence. Heat flow. Tectonic inversion. Holy Cross Mountains.**

INTRODUCTION

Classical outcrops of the Holy Cross Mountains (HCM) are among a few areas in Central Europe exposing a nearly complete succession of Phanerozoic strata. The long-studied Palaeozoic sections are of a key importance to understand the complex Phanerozoic development of the region bordering the East European Craton to the south-west (Dadlez et al., 1994; Lamarche et al., 1999; Pharaoh, 1999; Belka et al., 2002; Nawrocki et al., 2007). In the central part of the HCM area the Permian to Carboniferous strata are partly preserved in subordinate synclinal units whereas the unconformable Permian-Mesozoic succession is almost completely eroded (Fig. 1). At the same time, the interpolations of stratigraphy and lithofacies based on data from the Mesozoic outcrops surrounding the Palaeozoic core are hypothetical due to a complex regional variability in the depositional architecture and subsidence patterns (e.g. Kutek and Głazek, 1972; Hakenberg and Świdrowska, 1997; Lamarche et al., 1998). Therefore, the post-Devonian subsidence development of the HCM is poorly constrained and consequently the magnitude of Variscan and, particularly, latest Cretaceous-Paleogene inversion are disputable (Kutek, 2001; Lamarche et al., 2003b).

This study was designed to test, by means of numerical basin 1-D modelling, alternative variants of subsidence and uplift history of the HCM area from the Devonian to Recent in order to constrain quantitatively the amount of burial and ensuing inversion. Such an approach is intimately connected with a question of thermal history which is another debatable issue in the regional literature (Belka, 1990; Marynowski et al., 2002; Poprawa et al., 2005). Therefore, during the modelling procedure we evaluated also different scenarios of thermal evolution controlling the observed levels of thermal maturity in the Devonian and Permian-Mesozoic rocks.

REGIONAL SETTING AND OUTLINE OF GEOLOGICAL EVOLUTION

During the Devonian to Carboniferous, the HCM area was a part of the Variscan foreland, situated ca. 100 km

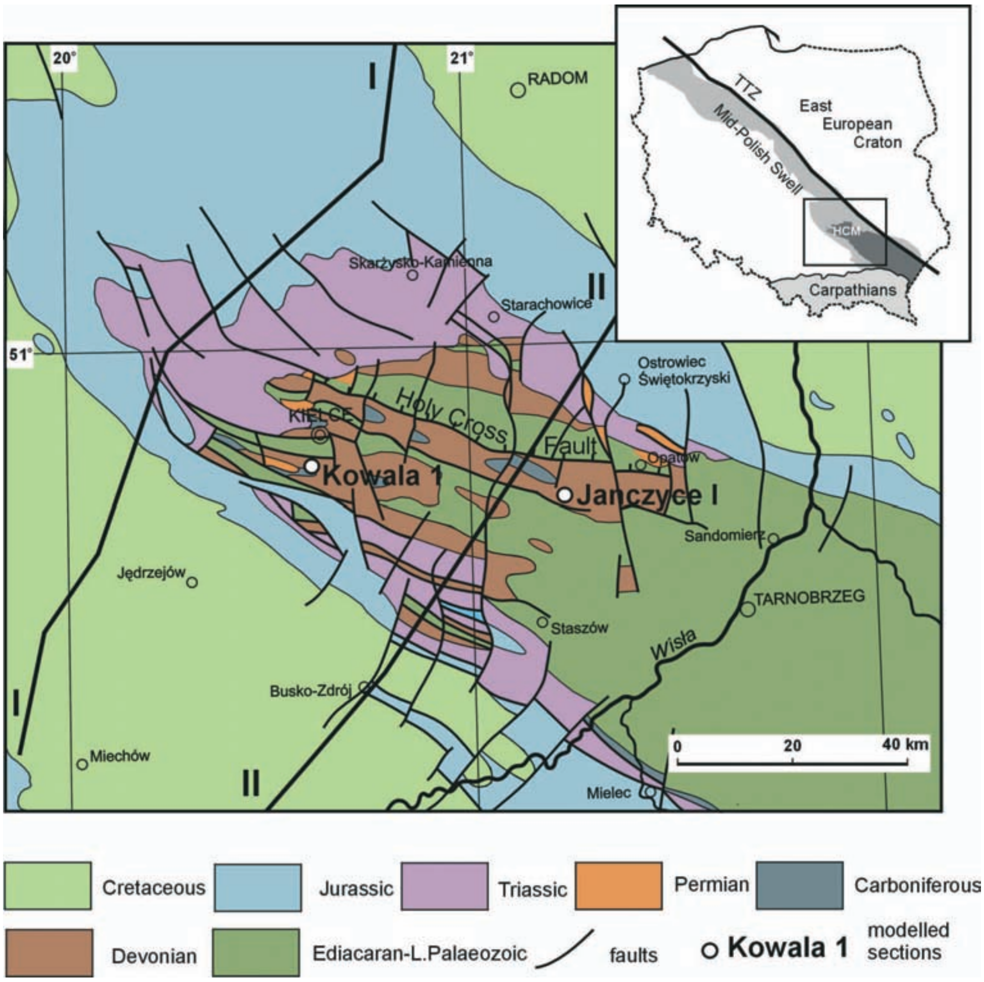

FIGURE 1 | **The inset map shows the location of the studied Holy Cross Mts. area (box) against the major regional units in Poland. The Mid-Polish Swell is outlined by the sub-Upper Cretaceous subcrops; dark grey - sub-Permian-Cenozoic subcrops. The sub-Cenozoic geological map (Dadlez et al., 2000) shows the location of the studied borehole sections Kowala 1 and Janczyce I, and the lines of palinspastic cross-sections (I-I, II-II; Kutek and Głazek, 1972) discussed in the text.**

east of the front of a thrust and fold belt (Dadlez et al., 1994; Narkiewicz, 2007). The investigated sections are located in the southern region of the HCM, south of the Holy Cross Fault (Fig. 1). This area underwent slow, gradually decreasing subsidence during the Devonian to Early Carboniferous (Narkiewicz, 2007). Sedimentary fill comprises up to 200 metres of Lower Devonian clastics overlain by about 1000 m of Middle to Upper Devonian shallow-water carbonates and deeper-shelf marly deposits (Szulczewski, 1995). These grade upwards into the Tournaisian to mid-Viséan black cherty shales (Zaręby Beds) with a local development of depositional gaps and Tournaisian condensed marly deposits (Radlin Beds) in the areas of former Upper Devonian reef complexes. The upper Viséan Lechówek Beds are characterised by an admixture of silty to fine sandy greywacke material in shaly strata (Żakowa and Migaszewski, 1995). The minimum primary thickness of the Lower Carboniferous is estimated at ca. 300 to 800 metres, and is rather poorly constrained due to repeated erosion and a lack of continuous sections. It is interpreted that the southern HCM region was uplifted near the transition from the Early to Late Carboniferous (cf. Narkiewicz, 2007). Later on, it underwent faulting and folding in a generally transpressive regime of the main inversion-phase in the late Westphalian-Stephanian (Lamarche et al., 2003a).

The Variscan unconformity, truncating different Lower to Upper Palaeozoic rocks, is overlain by a discontinuous cover of up to 200 m thick Permian (mostly Zechstein) sediments which mark the onset of the Late Permian-Mesozoic subsidence. The Zechstein is developed as nearshore to slightly deeper-marine facies succession (Kowalczewski and Rup, 1989) lacking thick evaporites typical for the Permian Basin depocenter north-west of the HCM area. It should be stressed that the Late Permian to Early Triassic extensional structures in the HCM area are not compatible with large-scale rift-type deformations (Kutek and Głazek, 1972; Lamarche et al., 1998). The magmatic phenomena of that age were not observed as well.

The Mesozoic succession, investigated mainly along the SW and N margins of the HCM area, comprises 2 to 3.5 kilometres of epicontinental deposits. They range from continental clastics (partly Lower and Upper Triassic, Lower Jurassic), to marginal marine facies (upper part of the Lower Triassic, Middle and Upper Triassic; Middle Jurassic, Lower Cretaceous), to open marine shelf carbonates of the Middle Triassic, Upper Jurassic and Upper Cretaceous (summarized in Marek and Pajchlowa, 1997; Dadlez et al., 1998). The sedimentation was punctuated by several minor erosional and(or) nondepositional events, attributed to so-called early and late Cimmerian tectonic phases (Kutek and Głazek, 1972; Głazek and Kutek, 1976). The former events are represented by minor unconformities at the Keuper-Rhaetian, Rhaetian-Liassic, and Liassic-Bathonian boundaries. The late Cimmerian movements are thought to be responsible for unconformities and associated gaps spanning the late Tithonian-?early Berriasian, and the later Early Cretaceous, preceding the late Albian transgression. The tectonic deformations connected with those events are generally insignificant and localized (Jaroszewski, 1972), whereas the associated erosion is minor relative to the preserved depositional record. Moreover, the sedimentary record becomes as a rule more complete towards the Palaeozoic core of the HCM, and thicknesses of individual stratigraphic units increase in that direction as well (Kutek and Głazek, 1972; Głazek and Kutek, 1976). This observation is consistent with the concept that the HCM area was part of the Mid-Polish Trough (Kutek and Głazek, 1972) which formed the NW-SE striking depocenter of the Permian-Mesozoic Polish Basin (Dadlez et al., 1995).

In the latest Cretaceous-Paleocene the HCM area underwent inversion along with other segments of the Mid-Polish Trough, to become the Mid-Polish Swell (see the inset map in Fig. 1). According to some authors (Kutek and Głazek, 1972; Hakenberg and Świdrowska, 1998) the inversion started during late Maastrichtian after a period of increased Late Cretaceous subsidence and sediment accumulation. Kutek (2001) postulated that the incipient uplift started probably in the late Senonian (?Maastrichtian) while the main uplift took place in the Paleocene. Recently, Świdrowska et al. (2008) interpret the onset of inversion during the early Maastrichtian. An opposite view assumes that the axial parts of the Mid-Polish Trough underwent inversion already since the Coniacian (Dadlez and Marek, 1997; see also Krzywiec, 2007, Krzywiec et al., 2009). A similar approach is adopted by Dadlez et al. (1998) who indicate a much thinner Upper Cretaceous in the present HCM. According to the latter authors also the total primary Permian to Mesozoic thickness in the HCM segment of the Mid-Polish Trough was lower than that assumed by Kutek and Głazek (1972). Consequently, the estimate of the inversion (=erosion) magnitude based on the interpretations given in Dadlez et al. (1998) is ca. 2500 metres, in contrast with 3000 to 3500 metres implied by the palinspastic restoration by Kutek and Głazek (1972).

Since neither Paleogene nor Neogene deposits have been encountered in the central parts of the Holy Cross Mts. it is generally assumed that the area in question underwent continuous erosion during the Cenozoic (Kutek and Głazek, 1972; Jarosiński et al., 2009). In the late Miocene, the HCM landmass formed a limit to the marine basin of the Carpathian Foredeep in the south. Thus, the present Palaeozoic outcrops of the HCM (see Fig. 1) developed as a cumulative effect of 1) relatively rapid erosion related to Late Cretaceous-Paleogene inversion and 2) prolonged, gradual denudation which has been taking place since the Eocene.

INPUT DATA

The present modelling was performed on two boreholes, more than 1 km deep, located in the southern region of the HCM (Fig. 1). Kowala 1 section comprises a complete fully cored Devonian succession while Janczyce I section lacks the Lower Devonian and upper Famennian parts (Fig. 2). Kowala 1 represents overall higher magnitude of the Permian-Mesozoic subsidence the rate of which is regionally dimnishing south-eastwards (Kutek and Głazek, 1972; Dadlez et al., 1998), i.e. towards the location of the Janczyce I. At the same time Janczyce I is located in the belt of increased thermal maturity of the Devonian as compared to the Kowala 1 setting (Belka, 1990; Marynowski, 1999). The sections are also representative of different Early Carboniferous palaeogeographic settings as Kowala 1 is located close to the Late Devonian-Early Carboniferous palaeoelevation (Szulczewski et al., 1996) while Janczyce I displays increased sediment-thicknesses in a more subsiding, shelf-basinal area.

Stratigraphy

The input data on the lower part of the modelled sections, marked by thicker vertical lines in the Fig. 2, were derived from direct observations of cores. The lithology and stratigraphy of the Devonian in the Kowala 1 section was described by Romanek and Rup (1990), and in the Janczyce I by Narkiewicz and Olkowicz-Paprocka (1983), Narkiewicz (1991), and Matyja and Narkiewicz (1995). The former section comprises 3 metres of the Tournaisian conformably overlying Famennian, whereas in the latter, the uppermost Famennian, estimated here at ca. 50 m, is missing below the thin Quaternary cover.

The stratigraphic input data on the eroded parts of the sections, including Carboniferous to Mesozoic, was based on different published sources. The Lower Carboniferous stratigraphy and lithology (Fig. 2) was restored using the regional data compiled by Żakowa and Migaszewski (1995). The estimates are better constrained for Kowala 1 than for Janczyce I due to better exposures and more refined stratigraphy in the south-western HCM as compared with the eastern area (Belka et al., 1996; Szulczewski et al., 1996).

The missing Permian-Mesozoic stratigraphy of the restored sections (Fig. 2) was based on two alternative interpretations: by Kutek and Głazek (1972), variant KG in Fig. 2, and by Dadlez et al. (1998), marked as variant A. The interpretations represent two contrasting approaches to the problem of the post-Variscan subsidence. Kutek and Głazek (1972) generally assume gradual increase of the subsidence rates toward the central part of HCM (=axial part of the Mid Polish Trough). On the other hand, Dadlez et al. (1998) give more conservative palaeothickness estimates in successive stratigraphic units, following earlier publications of the Polish Geological Institute (Marek, 1988; Marek and Pajchlowa, 1997).

Kutek and Głazek (1972) based their interpretations on palinspastic restoration of a palaeothickness of particular stratigraphic units in three cross-sections calibrated by deep boreholes situated north and south of the Palaeozoic core of HCM. The input data for the KG variant of the post-Carboniferous stratigraphy of the Kowala 1 borehole was calculated by an interpolation between cross-sections I-I and II-II (located in Fig. 1). In order to obtain the data for the Janczyce I we projected the borehole section on the closely located II-II cross-section.

The palaeogeographic atlas by Dadlez et al. (1998) includes interpreted sediment-thicknesses and lithology in a form of palaeothickness maps (mainly for the units of a series rank), and the lithofacies maps for narrower stratigraphic intervals. We constructed synthetic restored sections for the variant A by reading respective palaeothickness values and relevant lithofacies from the successive maps.

The stratigraphic schemes employed in both sources of data are directly comparable. The only significant difference is the inclusion of the Lower Keuper (= upper Ladinian) into the Röt-Muschelkalk complex by Dadlez et al. (1998), whereas this unit was combined into the Keuper-Rhaetian unit by Kutek and Głazek (1972). In most cases, the thickness of individual stratigraphic units by Kutek and Głazek (1972) is larger than that given by Dadlez et al. (1998). Two exceptions are the Upper Jurassic which is thinner by ca. 20 % (Kowala 1), and the Liassic which was interpreted by Kutek and Głazek (1972) as 40 m (Kowala 1) and 110 m (Janczyce I), in contrast with, respectively, 500 m and 600 m by Dadlez et al. (1998; Plate 36). Such a large Liassic thickness was obtained by interpolation based on a poorly constrained stratigraphy in a single well (A.Feldman-Olszewska, pers. comm., 2008). This thickness is also incompatible with the results of the palaeotectonic analysis of the SE segment of the Mid-Polish Trough (Hakenberg and Świdrowska, 1997; cf. also Świdrowska et al., 2008). The estimates by Kutek and Głazek (1972) are more reasonable in view of available data, and as such were exceptionally included also in variant A.

The early Cimmerian erosional episodes mentioned in the preceding chapter were not taken into account in the restored Mesozoic stratigraphy (Fig. 2) as their record is localized and quantitatively insignificant for the present considerations. In the KG scenario we assumed only a single erosional event in the late Tithonian (Kutek and Głazek, 1972) responsible for the erosion of ca. 100 m of middle Kimmeridgian to lower Tithonian. The stratigraphic gap comprising Hauterivian to mid Albian was interpreted as

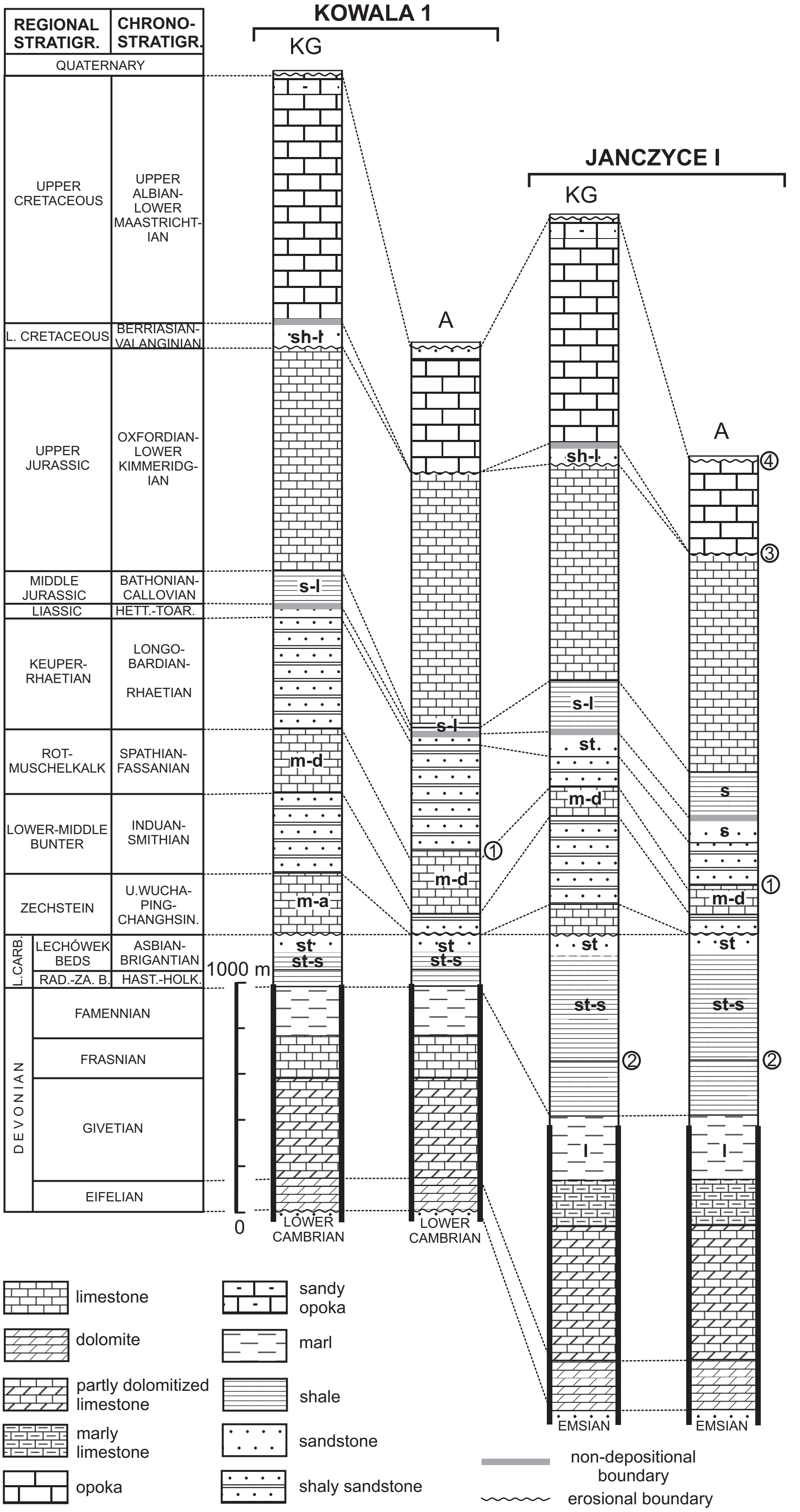

FIGURE 2 **Actual (thick vertical lines) and reconstructed stratigraphy of the Kowala 1 and Janczyce I well sections showing two variants of the eroded Permian-Mesozoic - after Kutek and Głazek (1972; KG) and Dadlez et al. (1998; A). Numbers in circles refer to the following stratigraphic boundaries: 1) Lower/Middle Keuper (= Carnian/Rhaetian); 2) Zaręby Beds/Lechówek Beds (= Tournaisian/lower Brigantian); 3) top lower Berriasian; 4) top Coniacian. Abbreviations: RAD= Radlin Beds, ZA= Zareby Beds. Letters in stratigraphic columns denote intercalations in the background lithology indicated by the pattern: a= anhydrite, d= dolomite, l= limestone, m= marl, s= sandstone, sh= shale, st= siltstone. Opoka is the regional term for the calcareous rock rich in authigenic silica of organic origin.**

a non-depositional hiatus. In variant A, Dadlez et al. (1998) interpreted a continuous sedimentation until Hauterivian. Consequently, the erosion spanning Barremian to mid Albian could have removed ca. 200 m of middle Kimmeridgian to Hauterivian sediments. In both variants the Lower-Middle Jurassic boundary is interpreted as a non-depositional surface spanning Aalenian-Bajocian times.

According to variant KG the Upper Cretaceous palaeothickness is as high as 1070 m and 990 m for the Kowala 1 and Janczyce I sections, respectively, while variant A assumes much smaller thicknesses (550 m and 400 m, respectively). The cross-sections restored by Kutek and Głazek (1972) do not include the Maastrichtian. However, they assume that the Late Cretaceous sedimentation continued until the early Maastrichtian and was then interrupted by the onset of inversion-related uplift. Consequently, a rather conservative eroded thickness of the Maastrichtian (100 m) was here assumed in the KG variant. Dadlez et al. (1998) interpreted the continuous Late Cretaceous subsidence until the Coniacian resulting in 500 m (Kowala 1) and 400 m (Janczyce I) of sediments. From the Santonian onwards, either reduced latest Cretaceous sedimentation (50 m; Kowala 1) or erosional regime (Janczyce I) is assumed in variant A.

Basing on the observations from the Pomeranian (NW) segment of the MPS (Resak et al., 2008) we can safely assume that the magnitude of erosion directly related to the inversion considerably exceeded the later, post-Paleocene denudation. For the purposes of the present modelling we had to ascribe certain magnitudes to both the erosional stages, based on poorly constrained interpretations. We assumed that the syn-inversion erosion is responsible for the removal of the entire Permian-Mesozoic succession in the case of the Kowala 1, which implies ca. 3700 m and 2500 m of inversion magnitude according to KG and A scenarios, respectively. For the sake of consistency we assumed the same numbers for the Janczyce I sections, which implies that ca. 500 m of the Lower Carboniferous was additionally eroded there.

Present-day heat flow

The present heat flow values were interpolated from a map of surface heat flow in Poland (Karwasiecka and Bruszewska, 1997). The respective values are: 46.4 mWm^{-2} for Kowala 1 and 49.5 mWm^{-2} for the Janczyce I well.

Thermal maturity data

The dataset employed for calibration (Table 1) comprised vitrinite reflectance (VR) values by Marynowski (1998). The data included nine values based on direct measurements (VRr). The remaining 15 values were calculated from the organic geochemical index MDR, applying the equation proposed by Radke and Willsch (1994). For several samples both measured and calculated (VRc) data were used.

The data for the Janczyce I borehole are based on core samples covering the entire Devonian succession although in a rather non-uniform manner mainly due to unfavourable lithology. In the Kowala 1 borehole fewer core-based values were available. Therefore we additionally used the data for two samples from the exposures located within a radius of 1 km from the borehole itself: Kowala Quarry and Sitkówka Kowala Quarry. As the stratigraphic position of the samples is well constrained they could be correlated with the borehole section (Table 1).

MODELLING PROCEDURES

Temperature and burial history of two investigated boreholes was modelled using PetroMod 10.0 software (1-D modelling). By means of this computer program a sequence of events that took place during basin evolution can be reconstructed starting from the oldest one. Each

TABLE 1 | **Vitrinite reflectance data used for calibration (Marynowski, 1998, Ph. D. thesis)**

Stratigraphy	Depth (m)	%VRr	%VRcalc
Janczyce I			
Famennian	52.0	0.72	0.63
Famennian	73.7	0.85	0.64
Famennian	137.4	0.82[a]	0.74
Famennian	229.7	0.86	0.81
Givetian	481.7		0.84
Givetian	705.1	0.99	1.12
Givetian	1011.0		0.71
Eifelian	1239.3	1.15	2.34
Kowala 1			
Famennian	39.8	0.55	0.55
Famennian[b]	110.0	0.53	0.58
Frasnian	318.8		0.68
Givetian/Frasnian[c]	410.0	0.63	0.61
Givetian	633.2		0.62
Givetian	732.5		0.68
Eifelian	955.5		0.64

%VRr - measured value

%VRcalc - calculated value based on the geochemical maturity index MDR (Radke and Willsch, 1994)

[a] - based on an insufficient number of measurements

[b] - Kowala Quarry

[c] - Sitkówka Kowala Quarry

event is described as a layer having particular thickness, lithology and deposition time given in Ma. For any eroded layer the time of erosion must be additionally defined. General principles of basin modelling can be found in Welte et al. (1997) while the detailed procedures and algorithms are described by Hantschel and Kauerauf (2008).

Two alternative sequences of events (variants A and KG) were modelled for each studied borehole section (Fig. 2). As a time framework we followed the Geologic Time Scale by Gradstein et al. (2004). Table 2 summarizes the petrophysical parameters of the particular lithological types included in our stratigraphic input data (compare Fig. 2). As petrophysical data from core measurements was not available for the studied wells, we employed the respective parameters for the corresponding rock types from the PetroMod database.

The temperature at the top and the bottom of the sediment fill was calculated by applying for subsequent time steps sediment-water interface temperatures (based on the time-latitude diagram by Wygrala, 1989) at the top of the section and heat flow values (in mWm^{-2}) at the base. The vitrinite reflectance evolution was modelled according to the Sweeney and Burnham (1990) algorithm.

In testing different heat-flow scenarios we took into account previous interpretations of the thermal history of the HCM area. Generally speaking, two alternative views have been proposed so far. Most authors (Belka, 1990; Marynowski, 1999; Narkiewicz, 2002) envision elevated Variscan, i.e. Carboniferous and, partly Permian, heat flow superimposed on steady low thermal regime similar to the present one. Conversely, Poprawa et al. (2005) proposed that the heat flow was constant and equal to the recent one throughout the Late Palaeozoic to Mesozoic, with superimposed Carboniferous-Permian and Late Jurassic episodes of localized hot-fluids circulation. They concluded that the assumption of elevated Variscan heat flow is not necessary to explain observed maturity of the Palaeozoic rocks.

MODELLING RESULTS

The results will be reported separately for the Kowala 1 and Janczyce I wells, which represent, respectively, higher and lower Permian-Mesozoic subsidence rates, regardless whether A or KG variant is assumed. Nevertheless, the difference in the amount of post-Carboniferous overburden cannot account for the patterns of organic maturity in the Devonian, which display opposite trends, i.e. increased values in the Janczyce I relative to the Kowala 1 (Belka, 1990; Marynowski, 1999; Table 1). Therefore, other factors were also taken into account, namely regional heat-flow variability through time, and, for the Janczyce I section, changes of the Carboniferous sediment thickness and

TABLE 2 | **Petrophysical properties of lithotypes applied in modelling.**

Lithology	Density [kg/m³]	Compressibility [1e-7/kPa]		Thermal Conductivity [W/mK]		Heat Capacity [cal/gK]	
		min.	max.	20°	100°	20°	100°
limestone	2710.0	10	150	2.83	2.56	0.195	0.223
dolomite	2836.0	10	250	3.81	3.21	0.202	0.229
partly dolomitized limestone	2773.0	10	200	3.32	2.88	0.199	0.226
marly limestone	2707.0	10	300	2.63	2.41	0.201	0.235
interbedded limestones, marls and dolomites	2720.3	10	239	2.87	2.58	0.197	0.226
interbedded limestones, marls and anhydrites	2717.1	9.1	372.4	2.85	2.57	0.197	0.227
marls with limestone interbeds	2698.5	10	545	2.53	2.34	0.202	0.235
opoka (silica-rich limestone)	2693.4	18	748	2.79	2.52	0.194	0.225
sandy opoka	2689.1	16	752	2.74	2.47	0.194	0.227
marl	2687.0	10	940	2.23	2.11	0.208	0.248
shale	2680.0	10	60000	1.98	1.91	0.213	0.258
shales with sandy/silty intercalations	2673.6	10	32500	2.26	2.09	0.202	0.243
shales with sandy/limestone intercalations	2683.0	10	24195	2.58	2.32	0.197	0.233
interbedded shales and sandstones	2669.0	10	2800	2.65	2.38	0.197	0.236
sandstone	2660.0	10	500	3.12	2.64	0.178	0.209
shaly sandstone	2666.0	10	1400	2.78	2.37	0.190	0.226
sandstones with shaly and limestone intercal.	2682.6	10	20023	2.65	2.37	0.195	0.230
sandstones-siltstones	2665.0	10	1900	2.59	2.31	0.192	0.229

Variscan erosion magnitude. In the further considerations the term "maximum temperatures during burial" (or simply "maximum temperatures") will refer to the lowermost calibrated unit, i.e. to the Eifelian strata. For a better understanding of our modelling approach the results are summarized in Table 3.

Kowala 1

When variant KG is assumed, the application of constant present heat-flow values causes a large misfit between the modelled curve and reflectance data (Fig. 3A, curve c). A good fit is obtained after assuming heat flow values lowered relative to the present ones by ca. 10-15 mWm^{-2} i.e. to 30-35 mWm^{-2} (Fig. 3A, curve a). An elevated Variscan heat flow is not necessary to obtain a good degree of consistency between calibration data and the calculated VR curve. However, the above modelling scenarios are tolerant to a Variscan heat flow elevated to values up to 80 mWm^{-2} (Fig. 3A, curve d).

For variant A application of constant present heat flow values provides a better agreement between the modelled curve and reflectance data (Fig. 3B, curve b). A good fit is obtained after assuming heat-flow values lowered relative

TABLE 3 | **Summary of modelling results for different variants of restored stratigraphy in studied wells, and for different heat flow scenarios.**

Well	Variant	Parameters	Results	
Kowala 1	KG	Constant, present HF ~ 45	Misfit	Fig. 3A, curve c
		Constant, lowered HF 30-35	Best fit	Fig. 3A, curves a,b
		Elevated Variscan HF Lowered "background" HF 30-35	Good fit until Variscan HF reaches 80	Fig. 3A, curve d
	A	Constant, present day HF ~ 45	Good fit	Fig. 3B, curve b
		Constant, slightly lowered HF 40	Best fit	Fig. 3B, curve a
		Elevated Variscan HF Slightly lowered "background" HF 40	Good fit until Variscan HF reaches 90	Fig. 3B, curve c
Janczyce I: "basic" model	KG	Constant, present day HF ~ 50	Misfit	Fig. 7A, curve b
		Constant, slightly lowered HF 45	Good fit	Fig. 7A, curve a
		Elevated Variscan HF 70 Slightly lowered "background" HF 45	Best fit	Fig. 7A, curve c
	A	Constant, present day HF ~50	Misfit	Fig. 7B, curve a
		Elevated Variscan HF 80 Present day "background" HF ~ 50	Best fit	Fig. 7B, curve b
Janczyce I: changing Lower Carboniferous thickness and Variscan erosion	KG	Thickness of L. Carboniferous reduced by 450 m Constant, present day HF ~ 50	Good fit	-
		Thickness of L. Carboniferous reduced by 450 m Elevated Variscan HF 90 Present day "background" HF ~ 50	Best fit	-
	A	Thickness of L. Carboniferous increased	Unrealistically low HF must be assumed to obtain satisfactory fit between curves	
		Thickness of L. Carboniferous reduced Constant, present day HF ~ 50	Unrealistically high Variscan HF must be assumed to obtain satisfactory fit between curves	
		Thickness of L. Carboniferous increased by 450 m Constant, present day HF ~ 50	Best fit	Fig. 10, curve a
		Thickness of L. Carboniferous increased by 450 m Slightly elevated Variscan HF 70 Present day "background" HF ~ 50	Misfit	Fig. 10, curve b
		Thickness of L. Carboniferous increased by 450 m Variscan erosion of 600 m Constant, present day HF ~ 50	Misfit	Fig. 12, curve a
		Thickness of L. Carboniferous increased by 450 m Variscan erosion of 600 m Elevated Variscan HF 75 Present day "background" HF ~ 50	Good fit	Fig. 12, curve b

Abbreviation: HF - heat flow (given in mW m^{-2})

to the present ones by ca. 5 mWm-2 i.e. to 40 mWm-2 (Fig. 3B, curve a). As in the variant KG, an elevated Variscan heat flow is not necessary to achieve a good correspondence with calibration data. However, the above modelling scenarios are tolerant to a Variscan heat flow elevated to values up to 90 mWm-2 (Fig. 3B, curve c).

The time-temperature distribution in the burial graphs demonstrates that both in the A and KG best-fit models assuming lowered constant heat flow, the maximum temperatures (ca. 90 ºC) are attained during the Late Cretaceous (Fig. 4A,B). The respective temperatures during the maximum Variscan burial (Viséan) are 55 ºC (KG) and 50 ºC (A). When the "permissible" elevated Variscan heat flow is applied (80 mWm-2), the Carboniferous temperatures are considerably higher, reaching ca. 95 ºC in both cases (variant A - Fig. 4C).

Janczyce I: "basic" model

The "basic" model assumes the Lower Carboniferous stratigraphy after Żakowa and Migaszewski (1995) shown in Fig. 2.

In the variant KG application of the constant present heat-flow values leads to modelled VR values that exceed those of the calibration data (Fig. 5A, curve b). To obtain an optimum fit a slightly lower constant heat flow of 45 mWm-2 had to be applied (Fig. 5A, curve a). An even better

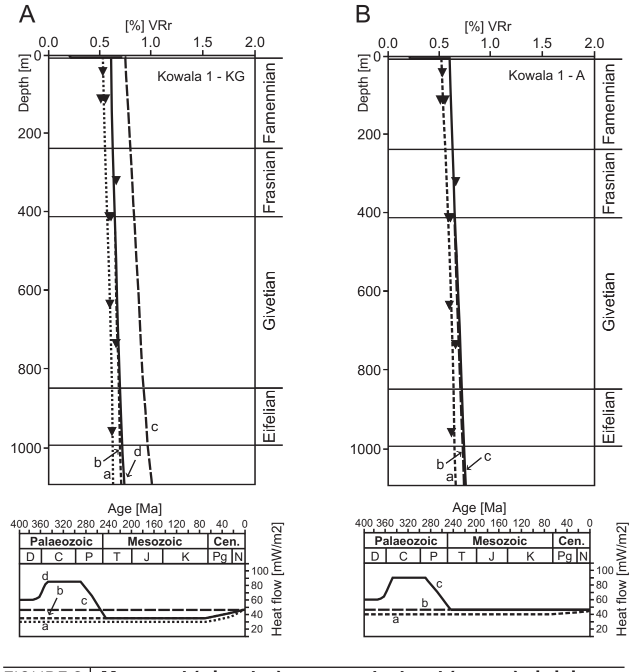

FIGURE 3 | **Measured (triangles) versus calculated (curves) vitrinite reflectance in Kowala 1 well for different heat flow histories. A) variant KG. B) variant A**

fit was attained when assuming a Variscan heat flow of 70 mWm-2 with the background value of 45 mWm-2 (Fig. 5A, curve c).

In variant A, when applying the constant present heat flow the modelled maturity is too low (Fig. 5B, curve a). In order to obtain the best fit, the Variscan heat flow was elevated to 80 mWm-2 (Fig. 5B, curve b).

Temperature-burial graphs of the best-fit models show roughly similar time-temperature trends for both variants (Fig. 6). The maximum Carboniferous temperature is slightly higher in A (ca. 140-145 ºC) than in KG (135 ºC). At the same time the maximum Late Cretaceous temperature shows the opposite trend, i.e. is 120 ºC (A) versus 140 ºC (KG).

Janczyce I: changing Carboniferous thickness and Variscan erosion

In a separate round of simulations we investigated the sensitivity of our models to changes in the primary thickness of the Lower Carboniferous and to an increased magnitude of the Variscan erosion, given that both variables are rather poorly constrained by the field data.

In the case of variant KG, reduction of Lower Carboniferous sediment-thickness by 450 metres (ca. 50 %) gives a good fit with VR data, which becomes even better when applying a considerably elevated Variscan heat flow of 90 mWm-2.

For variant A, a reduced thickness causes even a larger misfit than under assumption of both "basic" Carboniferous stratigraphy and present heat flow values (compare curve a in Fig. 5B). A rather unrealistically high Variscan heat flow has to be assumed to achieve a better fit in that case. The assumption of the Viséan strata thicker by 450 m (and therefore the entire Lower Carboniferous attaining 1290 m) gives a very good fit in the variant A, under conditions of the constant present heat flow (Fig. 7, curve a). However, such an assumption excludes the possibility of even slightly elevated Variscan heat flow (to 70 mWm-2) the application of which leads to a considerable misfit (Fig. 7, curve b). Moreover, it should be noted that 450 m of additional thickness assumed appears a maximum value as further thickness increase causes a significant change towards larger modelled reflectance values. To counterbalance this increase unrealistically low heat flow values would have to be applied. The best-fit model for the variant A (Fig. 7, curve a) implies that the maximum Carboniferous temperatures are 110-115 ºC and therefore much lower than 135 ºC calculated for the Late Cretaceous (Fig. 8).

A good fit may be achieved for the variant A when assuming increased Lower Carboniferous thickness and, at the same time, 600 metres of Variscan erosion instead of 100 m as in the "basic" model (see above). However, in that case a Variscan heat flow elevated to 75 mWm^{-2} is required (Fig. 9, curve b). The agreement is comparable or even slightly better than in the case of the "basic" model assuming Variscan heat flow elevated to 80 mWm^{-2}. The difference between both models with respect to time-temperature distribution is also negligible (compare burial graphs in Figs. 6B and 10). They both show maximum Carboniferous burial temperatures close to 140 °C whereas the maximum Late Cretaceous temperatures are lower, and reach 110 °C in the case of the "more sediment-more erosion" model (Fig. 10).

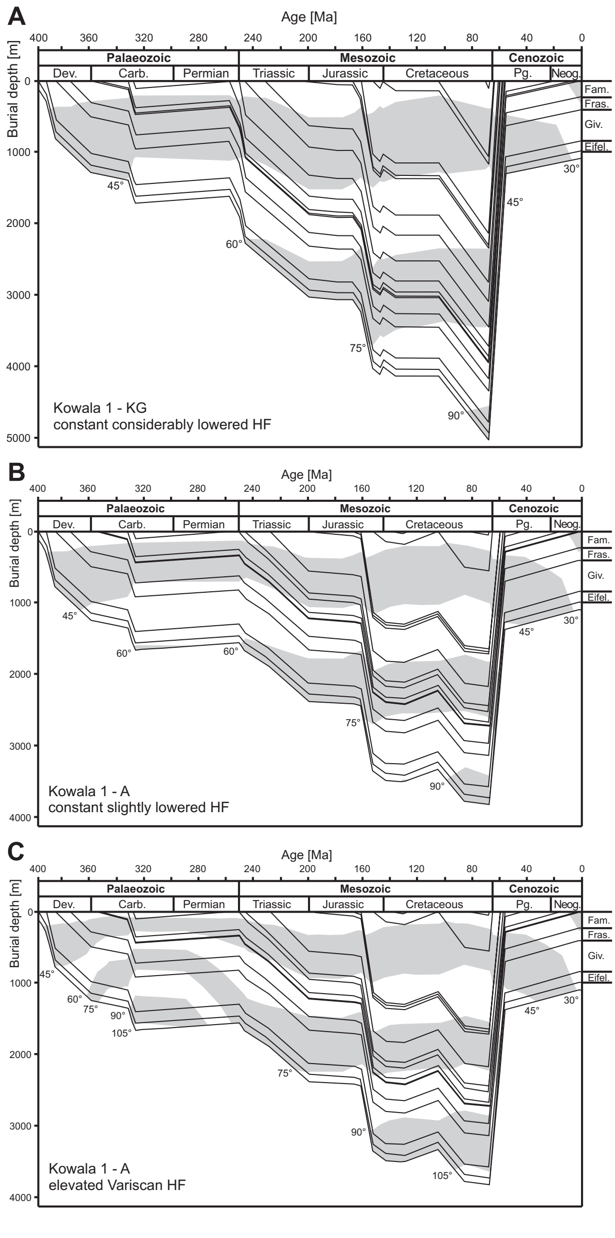

FIGURE 4 | **Burial graphs of Kowala 1 well. A) variant KG, constant considerably lowered heat flow (curve a in Fig. 3A). B) variant A, constant slightly lowered heat flow (curve a in Fig. 3B). C) variant A, elevated Variscan heat flow (curve c in Fig. 3B). Eifel.= Eifelian, Giv.= Givetian, Fras.= Frasnian, Fam.= Famennian.**

DISCUSSION

Elevated Variscan heat flow or larger eroded Carboniferous thickness?

Fig. 11 shows patterns of thermal maturity in the Devonian and Triassic based on vitrinite reflectance (Marynowski, 1999) and conodont colour alteration index (Belka, 1990; Narkiewicz and Malec, 2005). Although the Devonian patterns based on two indices do not strictly correspond to each other, they nevertheless show that the highest maturity (VR 1.25%; CAI 2.5-3.5) is found along the belt bordering the Holy Cross Fault from the south. Both VR and CAI gradually decrease southwards towards the minimum values of 0.50-0.65% (VR) and CAI 1 (Fig. 11). At the same time the Triassic (mainly Muschelkalk) data reveal a uniform maturity around 0.60% and CAI 1. Such a distribution led Belka (1990) and Marynowski (1999) to conclude that the thermal maturity of the Devonian-Carboniferous organic matter was attained before the Middle Triassic and most probably before the Late Carboniferous Variscan uplift. Moreover, Belka (1990) invoked an elevated Variscan heat flow with the geothermal gradient for the uppermost crust 2-3 times greater than the present-day one. Based on the distribution of vitrinite reflectance values with depth in the Kowala 1 and Janczyce I wells Marynowski (1999) interpreted that the latter section records influence of the Variscan palaeothermal anomaly associated with the Holy Cross Fault.

A different interpretation was presented by Poprawa et al. (2005) who concluded that the present-day maturity was attained during the Late Jurassic or, less probably, the Late Cretaceous. However, their conclusion is contradicted by the uniformly low organic maturity in the Triassic superimposed on a more complex pattern observed in the Devonian (Fig. 11). The reason for the apparent discrepancy between the regional maturity patterns and the results of the studies by Poprawa et al. (2005) may be due to the nature of their stratigraphic and maturity data. Their input data is compiled into "synthetic sections" representing areas tens of kilometres across and tied neither to actual field data nor to sources of information on the restored sediment thicknesses. Therefore, both stratigraphic and maturity data may be somehow incoherent.

The above discussion points to the fact that the thermal maturity of the Devonian-Carboniferous strata was largely attained before their erosion in the Late Carboniferous to Early Permian (see also Marynowski et al., 2002). Nevertheless, the significance of a possible thermal Variscan

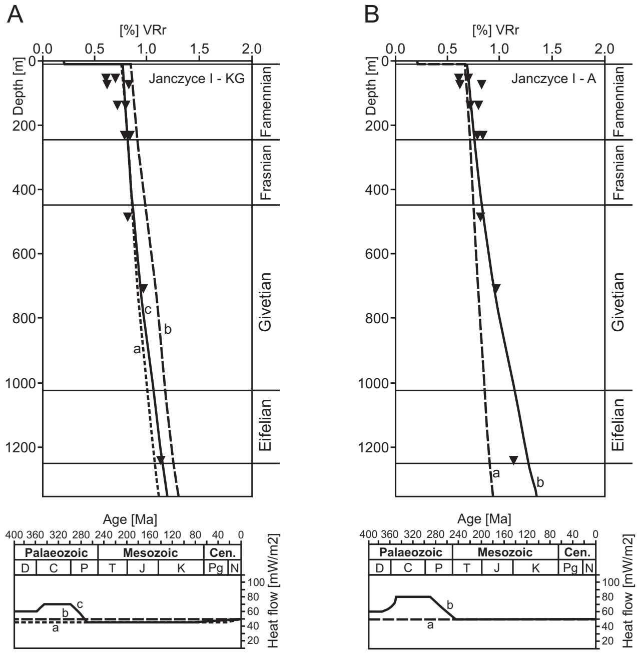

FIGURE 5 | **Measured (triangles) versus calculated (curves) vitrinite reflectance in Janczyce I well for different heat flow histories. A) variant KG. B) variant A.**

anomaly as the main controlling factor is less apparent. Clearly, the increase of vitrinite reflectance with depth is only at about 0.3% per km, which is a moderate value (see Tab. 1). High heat flow during times of maximum temperature would, however, lead to an increase of the maturity gradient (e.g. Littke et al., 1994; Senglaub et al., 2006). This is not visible in the data. Present modelling results demonstrate that the lateral changes in the primary distribution of the Lower Carboniferous thickness provide a viable alternative explanation especially when assuming scenario A of the lesser Permian-Mesozoic burial. In view of sparse stratigraphic data available, it is probable that the primary thickness of the Lower Carboniferous clastics could have attained in places up to 1200 to 1300 metres. The presently measured thicknesses may be considerably lower than primary ones due to prolonged erosion in the Late Carboniferous to Early Permian. According to our results, even a moderate thickness increase (less than 500 m) leads to a very good fit with the empirical maturity data, particularly if we assume a larger Variscan erosion magnitude. The high sensitivity of the model to increased Lower Carboniferous thickness results partly from the predominantly shaly-silty lithology with a considerable contribution of black shales. Small thermal conductivity of such sediments (Table 2) promotes an insulating effect thus leading to elevated thermal maturities in the underlying Devonian rocks. Similar mechanism was described by Cercone et al. (1996) for the Appalachian Basin.

Although the organic maturity pattern does not necessarily indicate an elevated Variscan heat flow, several lines of evidence support the hypothesis of a thermal anomaly during the Carboniferous to Permian times:

1) Hydrothermal sulphide (copper-polymetalic) mineralization is associated particularly with the Devonian carbonates mainly from the western HCM area, and ascribed to the Variscan (pre-Permian) stage of metallogenic development (Rubinowski, 1971).

2) Migaszewski et al. (1996) described widespread low-hydrothermal (50-80 ºC) calcite mineralization and associated hydrothermal karst dated as Permian (Lewandowski, 1999).

3) Pervasive mesogenetic dolomitization of the Middle to Upper Devonian carbonate platform is attributed to subsurface circulation of hot mineralized fluids (80-120 ºC) during the Carboniferous but preceding the Late Westphalian inversion (Narkiewicz, 1990; Narkiewicz et al., 2006). The secondary dolomites attain the maximum thickness of several hundred metres in a zone of increased thermal maturity south of the Holy Cross Fault.

4) Remagnetization of an Early Permian age is widespread in the Devonian carbonates displaying elevated thermal maturity. It is interpreted in terms of thermochemical processes related to cooling of a regional fluid circulation system (Grabowski et al., 2006).

The cited regional evidence supports the concept of an elevated heat flow that existed during the Late Carboniferous, and perhaps also in the Early Permian in the HCM area. Therefore, we conclude that the presently observed pattern of maturity of the Devonian in a belt south of the Holy Cross Fault (Fig. 11) most probably resulted from two independent factors acting in concert: 1) a primary thickness of the Lower Carboniferous higher by ca. 500 m relative to previous estimates, and 2) an elevated heat flow on the order of 70-80 mWm^{-2}. Higher primary thickness and more elevated heat flow appear to affect the results of the present modelling to an unacceptable extent. The modelled level of the Variscan heat flow is not unusually high if we take into account that the present heat flow ranges up to 90 mWm^{-2} in a tectonically stable area of SW Poland (Karwasiecka and Bruszewska, 1997; Królikowski, 2006). Heat flows calculated for Variscan Ruhr Basin and Rhenish Massif in Germany have been calculated to range from 60 to 80 mWm^{-2} (Büker et al., 1995; Littke et al., 2000), roughly the level that we interpret for the Holy Cross Mts.

The manifestations of an increased Late Carboniferous-Early Permian heat flow in the region of south-eastern

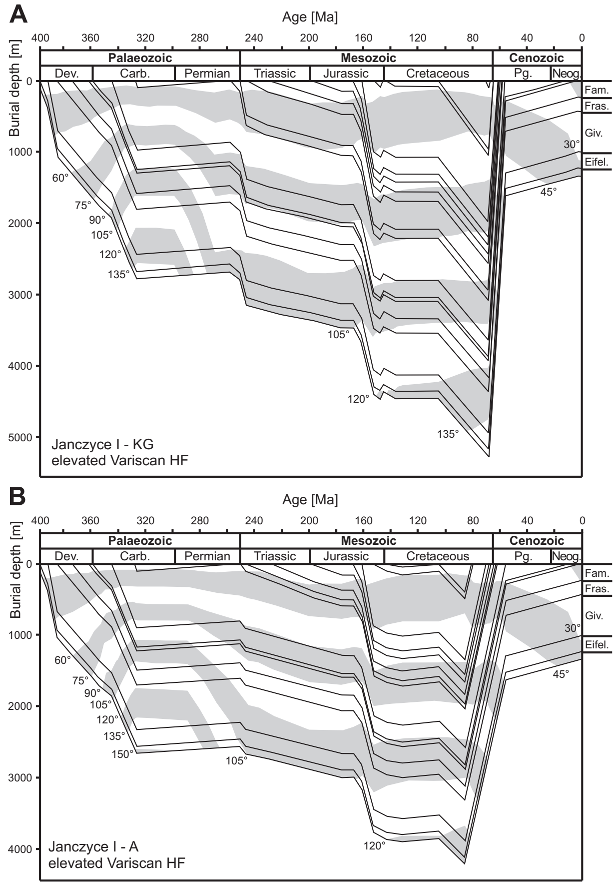

FIGURE 6 | **Burial graphs of Janczyce I well. A) variant KG, elevated Variscan heat flow (curve c in Fig. 5A). B) variant A, elevated Variscan heat flow (curve b in Fig. 5B). Other explanations - see Fig. 4.**

Mid-Polish Trough/Swell suggest that the high thermal regime was connected not exclusively with the areas of intense Stephanian-early Permian (305-290 Ma) magmatism known from the Variscan Orogen and its northern foreland including western Poland (recently summarized by Timmerman, 2008). The elevated Variscan heat flow apparently influenced also broad regions to the east, reaching as far as the Teisseyre-Tornquist Zone and probably even including a marginal (Lublin) part of the East European Craton (cf. Majorowicz et al., 1984).

The assumption of an elevated Variscan heat flow together with larger Carboniferous thickness appeared necessary to obtain a better fit with empirical data only in the case of the Janczyce I section. However, it should be stressed that the higher heat-flow values may be incorporated also in the Kowala 1 modelling (see above), although for the KG scenario this requires assuming a very low Mesozoic heat flow of 30 mWm^{-2}. The best-fit models of both scenarios, without elevated Variscan heat flow assumed, show remarkably low maximum burial temperatures (on the order of 50°C) for the entire Carboniferous-Permian time interval in the Kowala 1 borehole.

Permian-Mesozoic burial depth and magnitude of ensuing inversion

The variant KG of the Permian-Mesozoic geohistory, assuming a thicker post-Carboniferous sedimentary cover and larger magnitude of the latest Cretaceous-Paleogene inversion, generally requires a heat flow regime lower then the present one in order to fit the calibration data. In this scenario increasing either Variscan heat flow or primary Carboniferous thickness (or both) will move the modelled vitrinite reflectance curve towards higher values, thus increasing the misfit. This is particularly true for the Kowala 1 section (Fig. 3A) in which the organic maturity of the Devonian is lower while the Permian-Mesozoic overburden has been as high or higher than in the Janczyce I section (Fig. 2). To obtain a satisfactory fit with the calibration data the heat flow has to be lowered to

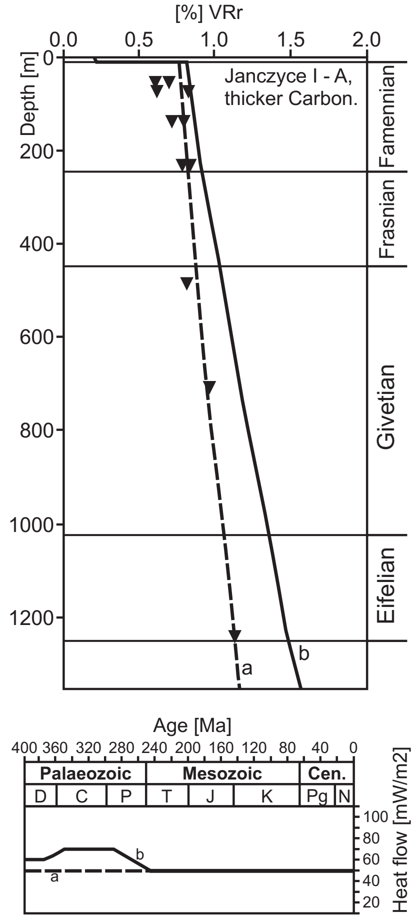

FIGURE 7 | **Measured (triangles) versus calculated (curves) vitrinite reflectance in Janczyce I well for different heat flow histories - variant A assuming thicker Lower Carboniferous.**

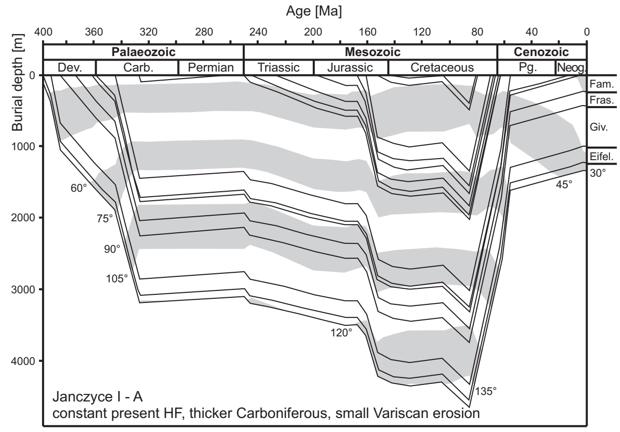

FIGURE 8 | **Burial graph of Janczyce I well, variant A assuming thicker Lower Carboniferous and constant present heat flow (curve a in Fig. 7). Other explanations - see Fig. 4.**

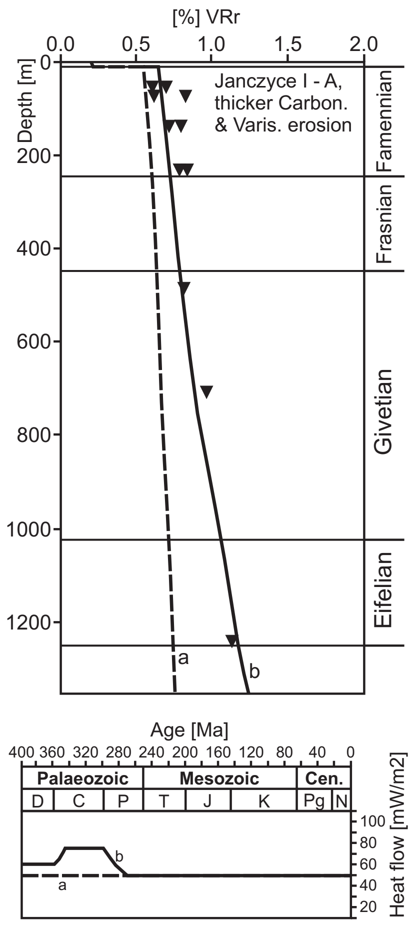

FIGURE 9 | **Measured (triangles) versus calculated (curves) vitrinite reflectance in Janczyce I well for different heat flow histories - variant A assuming thicker Lower Carboniferous and significant Variscan erosion.**

30-35 mWm^{-2} which is considerably less then the present-day value.

We conclude that, based on the Kowala 1 section, variant A is more acceptable than variant KG, which means that the total Permian-Mesozoic subsidence and ensuing inversion were lower than those assumed by scenario KG. This further implies that the Late Cretaceous-Paleogene inversion probably started earlier than in late Maastrichtian, presumably in the Santonian. These conclusions are similar to the results of modelling in the Pomeranian (NW) segment the MPS (Resak et al., 2008). According to these authors, the total Upper Cretaceous thickness ranged to 200-300 metres as compared to 400-550 m in our variant A. The inversion in NW Poland most probably started in the late Turonian or Coniacian, i.e. slightly earlier than implied by the interpretation of Dadlez et al. (1998) for the HCM area. It should be noted, however, that recent seismostratigraphic interpretations by Krzywiec (2007) also point to the ?Turonian-Coniacian onset of inversion processes in the Holy Cross Mts. area as well.

The results of the modelling of the Janczyce I borehole are less conclusive with respect to the validity of either variant. Here, in contrast to Kowala 1, the higher levels of organic maturity in the Devonian do not require drastic reductions in the Mesozoic heat flow, because the present level of organic maturity was already almost reached in the Late Carboniferous/Early Permian and not overwhelmed by later Cretaceous maturation as in the case of Kowala 1. However, high rates of the Permian-Mesozoic subsidence asssumed by the KG variant limit the possibility to include an elevated Variscan heat flow - in fact a maximum value of only 70 mWm^{-2} would be in accordance with scenario KG in this case. In the Kowala 1 section much lower calculated maximum burial temperatures for the Carboniferous-Permian are consistent with both lower organic maturity

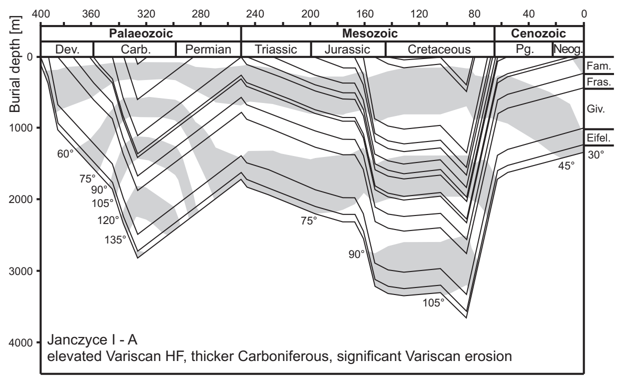

FIGURE 10 | **Burial graph of Janczyce I well, variant A assuming elevated Variscan heat flow, thicker Lower Carboniferous and significant Variscan erosion (curve b in Fig. 9). Other explanations - see Fig. 4.**

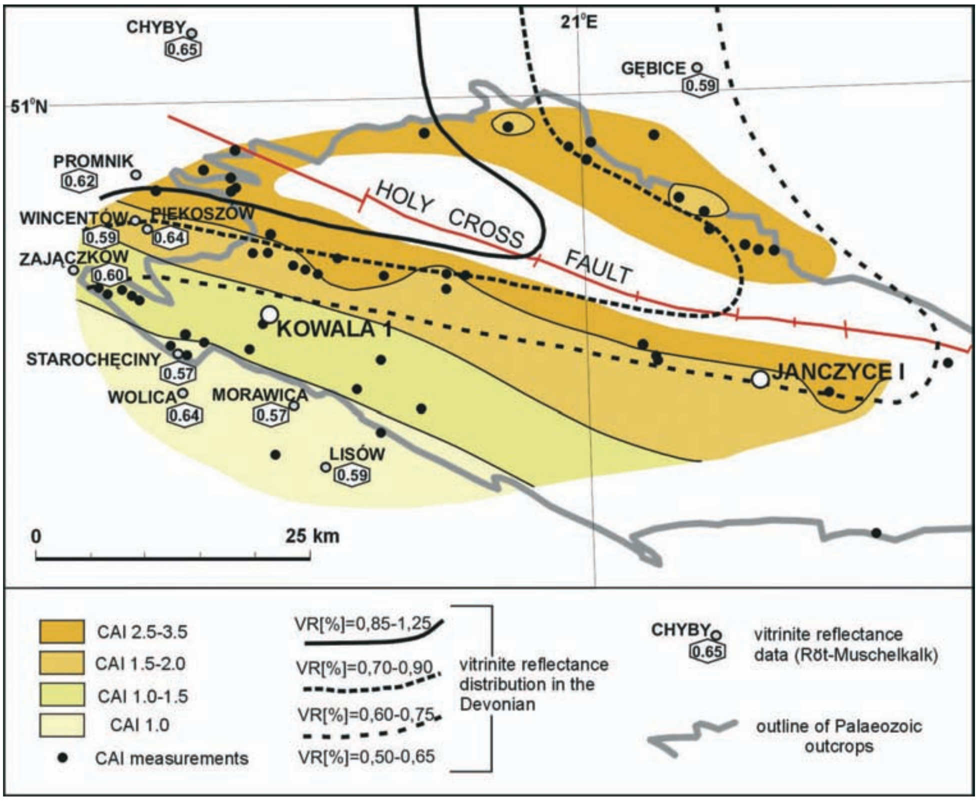

FIGURE 11 | **Thermal maturity map of the Devonian in the Holy Cross Mts. based on CAI (Belka, 1990; Narkiewicz and Malec, 2005) and vitrinite reflectance data calculated from biomarker indices (Marynowski, 1999). Data for the Röt and Muschelkalk - from Marynowski et al. (2002). Note location of the Kowala 1 and Janczyce I boreholes.**

and other geological evidence indicating a cooler thermal regime (dolomitization, palaeomagnetic data).

CONCLUSIONS

The burial-thermal modelling of two investigated borehole-sections in the Holy Cross Mountains demonstrates that the present maturity of the organic matter in the Devonian was controlled by several independent factors.

Two investigated, alternative variants of the post-Carboniferous geohistory, assuming different thicknesses of the eroded sedimentary section and varying magnitude of the Late Cretaceous-Paleogene inversion, satisfy the requirements of the thermal-burial models, although with different additional assumptions. For variant KG, which implies thicker Permian-Mesozoic units and higher inversion magnitude (Kutek and Głazek, 1972), these assumptions include lowering of the heat flow down to hardly acceptable values (Kowala 1) or lead to limited possibility of incorporating elevated Variscan heat flow and(or) increased Carboniferous thickness (Janczyce I). Variant A (Dadlez et al., 1998), on the other hand, allows more realistic assumptions regarding heat flow development through time, including an ample possibility to incorporate elevated Variscan heat flow.

The modelling results are consistent with the assumption of a moderate to slightly elevated Variscan (Carboniferous-Early Permian) heat flow on the order of 70-80 mWm^{-2}, particularly in an elongated zone south of the Holy Cross Fault. The hotter thermal regime is further confirmed by several regional evidences, including mineralization, mesogenetic dolomitization, hydrothermal karst and thermochemical remagnetization. The regional data, supported by the present modelling results, indicate that the Late Carboniferous-Early Permian high-thermal regime extended beyond the area of late Variscan magmatism in Central Europe. The localised zones of elevated heat flow may have been controlled by intermittently reactivated crustal discontinuities such as the Holy Cross Fault, reaching eastwards as far as the TTZ and marginal parts of of the East European Craton.

It seems likely that increased organic thermal maturity in the Devonian was at least partly the result of an increased Carboniferous sediment thickness. Previously interpreted thicknesses could have been underestimated by up to 500 m. This "additional" thickness could have been eroded during the Late Carboniferous to Early Permian. The insulating effect of the Carboniferous overburden on the Devonian maturity was enhanced by the predominantly shaly-silty lithology.

The acceptance of the variant A (Dadlez et al., 1998) implies that the total Permian-Mesozoic burial in the Holy

Cross Mts. area was on the order of 2000-2500 metres rather than 3000-3500 metres proposed by Kutek and Głazek (1972). Upper Cretaceous thickness could have been 400 to 500 m instead of ca. 1000 m, whereas the latest Cretaceous-Paleogene inversion more likely started earlier, in the Santonian, and not in the late Maastrichtian. This timing of inversion would be identical (within the limits of resolution) with the start of inversion of Variscan massifs and Mesozoic basins such as the Lower Saxony Basin further west (Senglaub et al., 2005; Senglaub et al., 2006; Petmecky et al., 1999; Voigt et al., 2009).

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