Geologie en Mijnbouw **76:** 271–275, 1997.

Short Communication

Coalification anomalies induced by fluid flow at the Variscan thrust front: A numerical model of the palaeotemperature field

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Received 24 December 1996; accepted in revised form 16 July 1997

Key words: palaeofluid flow, thermal simulation, Variscan foreland, vitrinite reflectance

Introduction

The organic rank in the northern Variscan foreland (Nordeifel foreland, western Germany) has recently been used as a palaeotemperature indicator in basin modelling and studies of orogenic processes (e.g. Büker et al. 1996). Teichmüller & Teichmüller (1979) determined vitrinite reflectance in Lower Palaeozoic to Upper Carboniferous rocks of the Variscan orogen (Figure 1A). They noticed locally anomalous high coalification values in Upper Carboniferous sediments of the Wurm syncline in front of the Aachen thrust fault. The coalification range is similar to the organic rank in older sediments (Devonian to Namurian) of the Aachen and Inde nappes (Figure 1A). In the northeastern part of the Wurm syncline, vitrinite reflectance decreases to a value of 1.4% Rm. Based on the kinetic model of Sweeney and Burnham (1990), maximum coalification temperatures of ~ 210 °C caused the high vitrinite reflectance of 2.6% Rm, assuming a thermal event of ten million years (Bayer et al. 1995). Low-salinity fluid inclusions in quartz veins have similarly high temperatures and are probably related to the Variscan orogeny (homogenization temperatures of fluid inclusions up to 210 °C, Stroink 1993).

Büker et al. (1996) showed by a 1D-thermal simulation that a burial depth of 2.6 to 3.3 km is required to obtain a vitrinite reflectance of 1.2% Rm in the Upper Westphalian A and the coalification gradient measured in the Floverich 2E-1 well in the northeastern part of the Wurm syncline. In their model this maximum burial was caused by an important Upper Carboniferous sedimentation or by Variscan nappe stacking. In addition, an increased heat flow up to ~ 90 mW/m^2 was required.

The model of Büker et al. (1996) simulates the palaeogeothermal situation in the northeastern part of the Wurm syncline. It does not account for the anomalous coalification values present in the Upper Carboniferous sediments in the central part of this syncline. In this context the structural setting is essential. The most recent structural model interprets the Nordeifel foreland as a thin-skinned tectonic setting with considerable nappe stacking and strong imbrication at the thrust front (Winterfeld and Walter 1993, Figure 1B). Within this geological setting, the palaeofluid flow model of Oliver (1986) might be applicable. In this model, fluid migration into the foreland is induced by orogenic compression and accounts for e.g. an increased coalification due to supplementary heat transport.

We present a 2D-thermal model of the Nordeifel foreland which simulates the coalification high in the Wurm syncline. In contrast to the model of Büker et al. (1996), the numerical simulation incoporates heat transport by fluid flow and by thermal conduction. The simulation applies and specifies the geological and thermophysical conditions of the palaeogeothermal field, which has been calibrated by the vitrinite reflectances of the Westphalian strata in the central Wurm syncline.

Model

In the present model, a syn- to postorogenic age of the coalification event is assumed. With respect to

Table 1. Range of petrophysical parameters applied in the computer simulation.

	Thermal conductivity (W/K m)	Permeability (mDarcy)
Upper Carboniferous	1.8–2.1	5.0
Lower Carboniferous & Devonian	2.0–2.5	0.01–2.4
Lower Palaeozoic	3.5	0.001–0.01
Fault zones	2.1	5.0–500.0

the high palaeotemperatures, indicated by the vitrinite reflectance data in the Wurm syncline, coalification probably occurred during maximum burial related to Variscan thrusting and subsequent sedimentation in front of the orogen. After the denudation of the Palaeozoic rocks in post-Variscan times only minor sedimentation took place. The model considers heat transport by forced fluid flow along highly permeable fault zones as a possible cause of the anomalous high coalification. The fluid flow event itself could have been active during Variscan thrusting (synorogenic), but also later (postorogenic) in a still deep burial realm. This corresponds to a syn- to postorogenic age.

The section modelled is shown by line M-M′ in Figure 1B. It includes the external part of the allochthonous structure with the imbricate deformation front and the autochthonous Wurm syncline. For the simulation of the palaeotemperature field, the present-day structure along section M-M′ has been modified by a rock overburden of 2.7 km in the north (reconstructed thickness of overlying Upper Carboniferous sediments) and up to 4.2 km in the south (predominantly Devonian rocks). Palaeotemperatures of 210 °C (2.6% Rm) and 195 °C (2.2% Rm) in the Westphalian sediments have been determined (Teichmüller & Teichmüller 1979, Bayer et al. 1995) and are applied to calibrate the model. These coalification temperatures were obtained taking into account a thermal event of ten million years. A shorter duration requires higher temperatures for the same vitrinite reflectances.

The rocks in the area studied consist of Lower Palaeozoic low-grade metamorphosed sediments, Devonian carbonates, shales and sandstones, Lower Carboniferous carbonates and Upper Carboniferous shales, sandstones and coals. An appropriate value for the thermal conductivity and the permeability has been assigned to each major lithological unit in the area. The material parameters are based on mean petrophysical

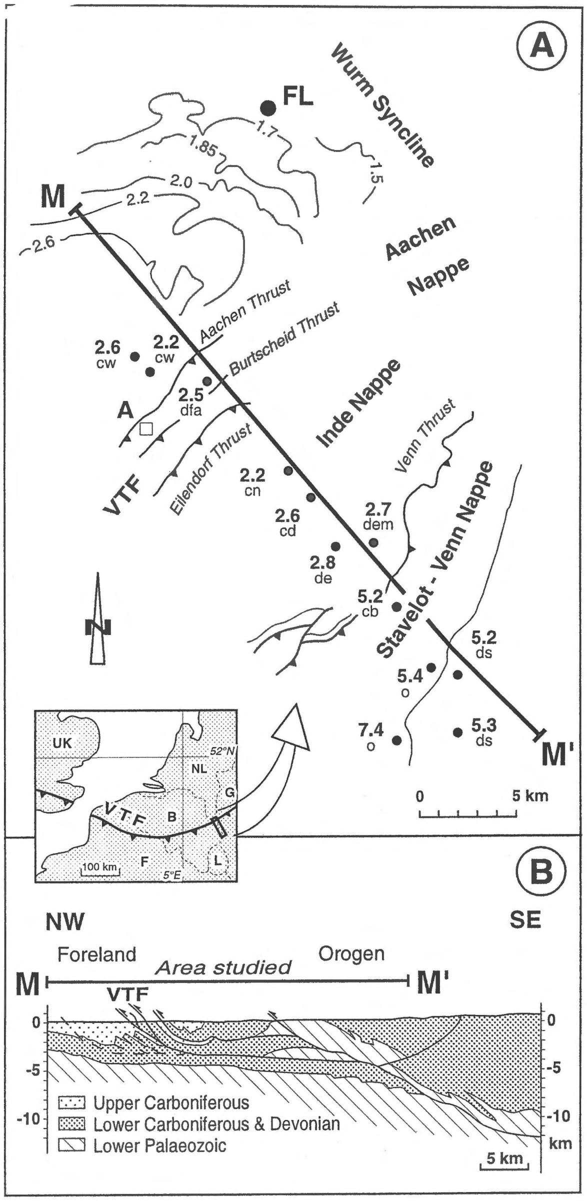

Figure 1. A) Map of vitrinite reflectance (% Rm) at the Variscan thrust front. The isolines of vitrinite reflectance in the Wurm syncline are for the Upper Westphalian A strata (after Babinecz, 1962 and Teichmüller and Teichmüller, 1979). B – Belgium, NL – Netherlands, G – Germany, L – Luxemburg, F – France, UK – United Kingdom, VTF – Variscan thrust front, cw – Westphalian, cn – Namurian, cd – Dinantian, dfa – Famennian, de – Eifelian, dem – Emsian, ds – Siegenian, o – Ordovician, cb – Cambrian, FL – well Floverich 2E-1, A – Aachen. B) Simplified structural model of the Nordeifel foreland (after Winterfeld and Walter, 1993).

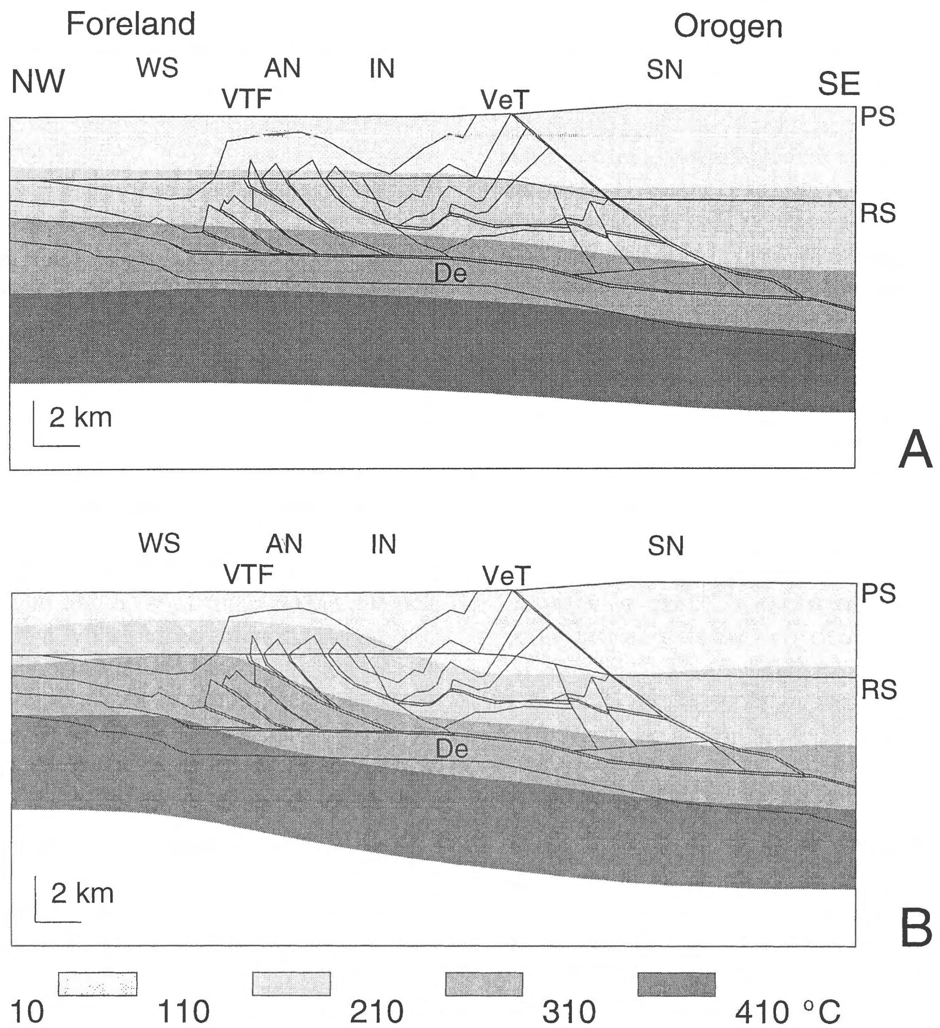

Figure 2. A) Temperature distribution along line M-M′ of Figure 1, with only conductive heat transport (basal heat flow of 90 mW/m^2). WS – Wurm syncline, AN – Aachen nappe, IN – Inde nappe, SN – Stavelot-Venn nappe, VTF – Variscan thrust front, VeT – Venn thrust, De – detachment fault, PS – palaeosurface, RS – recent surface. B) Temperature field modified by fluid flow, explaining the high coalification temperatures in the Wurm syncline. (See text for area south of Wurm syncline.)

properties published by Angenheister (1982). The values applied range from 1.8 to 3.5 W/K m for thermal conductivity and from 0.001 to 5 mDarcy for permeability with exception of certain fault zones (detachment and most northern imbricate zone), where higher permeabilities are assumed (500 mDarcy). The permeability of these zones may even be enhanced by the presence of karstified carbonates. Table 1 summarizes the data applied within the major stratigraphical units and the fault zones. The ranges take into account variations of the lithology (defined as major lithological units) within the stratigraphic systems. The numerical model is solved by the Finite Element Method (FEM) and includes the equation of coupled heat and fluid transport (Bayer et al. 1995).

Results and discussion

The aim of this study is to simulate the vitrinite reflectances measured in the Upper Carboniferous sediments of the central Wurm syncline. The vitrinite reflectance data of the older strata of the Inde nappe and of the Stavelot-Venn nappe are not explained in the present model. Coalification within these strata most likely occurred preorogenically (Teichmüller &

Teichmüller 1979, Oncken 1990, Helsen & Königshof 1994) and this has not been included in the simulation.

A scenario of the palaeogeothermal field has been modelled applying an increased basal heat flow density of 90 mW/m^2. This is according to Allen and Allen (1990) a reasonable value for compressional basins. It clearly exceeds the mean continental heat flow of 60 mW/m^2 in stable areas. Similar high heat flow densities are needed to explain the lower coalification values and the coalification gradient in the northeastern part of the Wurm syncline (Büker et al. 1996).

Figure 2A shows the temperature distribution with solely conductive heat transport. Laterally, the temperature gradients differ due to the change in thermal conductivities. In the Wurm syncline, shaly and coaly sediments with low thermal conductivities cause relatively high temperature gradients. Nevertheless, only a temperature of ~ 130 °C can be reached at the level of the present-day surface (depth of 2.7 km in the palaeomodel), which is much too cool. Within this model higher temperatures can only be obtained by unrealistic burial depths or even higher basal heat input.

The lateral temperature difference increases by the incorporation of fluid flow in the numerical model (Figure 2B). Coupled heat transport induces a geothermal 'high' of 210 °C at the location with the anomalous coalification values in the Wurm syncline. The palaeothermal gradient is ~ 70 °C/km. Due to the hydraulic gradient, fluids migrate in northern direction and heat transport depends on flow velocities. Pathways for high flow velocities are certainly the permeable fault zones. Therefore, the temperature distribution mainly relies on the high permeabilities in the fault zone along the detachment and in the most northern imbricate zone. The high permeabilities in the fault zones are likely caused tectonically and they may be enhanced by karstification of the carbonates. The timing of the fault activity is likely late orogenic (final imbrication) or postorogenic (reactivation of faults). In the scenario, hot fluids enter from the south along the detachment zone. The heated fluids ascend in the Wurm syncline and warm up the wall-rock by flow velocities in the order of metres per year (steady-state simulation). Although, the model nicely approximates the palaeotemperature data deduced from the vitrinite reflectance, it still lacks factors such as temperature and fluid flow modifications with time and the effect of convection by varying fluid densities.

The numerical stimulation implies that an important fluid discharge occurred in the footwall of the Variscan thrust front. An upward fluid flow along fractures and faults at the Variscan front in eastern Belgium has also been suggested by Zhang et al. (in press) based on the precipitation temperature of chlorite in shear veins. High fluid discharges have not been observed to the west of the strongly imbricated zone, where a Lower Palaeozoic basement (Sambre-Meuse Massif) is involved in the Variscan thrust front (Muchez et al. 1995). The frontal thrust splay seems to provide the necessary pathways for major fluid migration.

Conclusions

An anomalous coalification pattern in the sub-Variscan foredeep can be explained by a local increase in the temperature induced by forced fluid flow along thrust faults. Major fluid flow occurred through the frontal thrust splay. The boundary conditions of the numerical simulation are 90 mW/m^2 for the heat flow and 500 mDarcy for the permeability in the fault zones. Decreasing the basal heat flow would require either deeper burial or enforced heat transport by fluids to obtain the same palaeotemperatures. In the scenario, realistic flow velocities in the order of metres per year along the fault zones have been calculated and are necessary to simulate the observed palaeotemperature distribution. The modelled palaeotemperature field reflects the coalification temperatures indicated by vitrinite reflectance data of Upper Carboniferous sediments in the central Wurm syncline. The model does not explain the vitrinite reflectances present in older Palaeozoic rocks south of the Wurm syncline, which are probably dominated by preorogenic thermal influences.

Acknowledgements

We are especially grateful to J. Springer, GFZ Potsdam, who developed the FEM software. We also thank H. Visscher and W. Visser for their stimulating and constructive reviews. The numerical simulation was performed for the Bundesministerium für Bildung und Forschung (BMBF) within the project-no. 0326761A. The responsibility for the study remains with the authors. B. Lünenschloss thanks the Research Fund of the K.U. Leuven for a research grant, during which this paper has been prepared. Ph. Munchez is a senior research associate of the Fund of Scientific Research of Flanders (Belgium).

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