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Lithofacies analysis of Miocene sediments in the southern part of Carpathian Foredeep, based on the re-interpretation of drill logging data

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Abstract. Miocene sediments were studied based on the examination of drill logs, drill cores and seismic reflection profiles from the southern part of the Carpathian Foredeep in Moravia. Thirteen well log facies were recognized in the southern part of the Carpathian Foredeep based on the evaluation of well log measurements, the lithological study of drill cores, and seismic profiles. The selected well log facies are used for characterising the basin structure during its development. Maps of the thicknesses of the well log facies were produced that allow to illustrate five stages of basin development. Individual stages also reflect the controlling factors of basin and depositional space formation.

Key words: Carpathian Foredeep, Miocene, sedimentary structure, drill logging, well log facies interpretation, facies analysis, basin development

Introduction

The main goal of this paper is to characterise the Miocene sedimentation of the southern part of the Carpathian Foredeep in the southern Moravian region of the Czech Republic (Fig. 1). Lateral and vertical facies changes were studied using well log data and drill cores to estimate the Miocene coastline position and its migration through time, as well as to document the development of foredeep depocentres filled by the shallow marine deposits during that time.

The main sources of data used in formulating the facies structure and possible sequence stratigraphy of the southern Carpathian Foredeep were well logs of the Miocene sediments obtained from drillings in this area. The determination of well log facies, based on the study of their composition, allowed the comparison of individual parts of the drill profiles and the identification of missing strata.

The well log data was re-studied in the interest of formulating new lithological interpretations and identifying sections with matching characteristics. The wider purpose of this work was the establishment of unified criteria toward identifying "homogenous" complexes that would be amenable to comparison with individual sections from various boreholes. The methods by which well logs are studied (including electrical, nuclear, and acoustic methods) reveal the quantitative and qualitative properties of the facies they represent. Although well log data do not include direct stratigraphical information of the facies through which they pass, such data nonetheless enable a better evaluation and comparison of facies development than do the majority of surface outcrops. Specifically, well log records may be used toward studying the development of the parameters of interest with regard to depth. This allows us to define specific well log sequences. In some cases, the shapes of a band of well log layers indicate the development of sedimentary environments quite precisely. We thus identified well log facies based on the shape and direction of the well log curves.

The southwestern part of the Carpathian Foredeep has been studied by numerous authors, and various opinions exist about its detailed stratigraphy and lithology (Brzobohatý and Cicha 1993, Cicha 1995, Čtyroký 1991, Jiříček 1995, and other authors). Well log data were used for facies studies in middle and northern part of the Carpathian Foredeep by Pálenský et al. (1995a, b).

Geological setting

The Carpathian Foredeep occupies a large area of the Moravian shallow valleys, and the Vyškov and Moravian gates, including the areas around the towns of Ostrava and Opava. It continues south to the Austrian Molasse Zone and north to the foredeep in Poland. Relics of the Lower Badenian basin reach the Czech-Moravian Highland, the Drahany Upland, the Boskovice Furrow, and the Lower Jeseník Mountains. The structure of the Carpathian Foredeep was tectonically influenced mainly by an old system of tectonic lines in NE-SW and NW-SE directions, which, at different times, variously contributed to the creation of partial depressions and elevations (Brzobohatý and Cicha 1993).

The Carpathian Foredeep may be classified as a peripheral foreland basin (Nehyba 2000). It developed on the southern slopes of the European Platform due to collision with the Carpathian orogen during the Miocene. The basin running along the Carpathian chain had an asymmetric form, the deeper part of which was in front of the overriding accretionary wedge (Outer Western Carpathians). The gently inclined slope was built up by the platform margin, while the opposite, more steeply inclined slope resulted from the piling of thrust nappes situated in the south of the Outer Carpathian nappe pile. The migration of depocentres occurred from west to east along the orogen loop, following the retreat of subduction and detachment of the down-going plate (Tomek and Hall 1993).

The westernmost part situated in southern Moravia developed during the tectonic extrusion of the Western Carpathians from the Eastern Alpine domain, associated with oblique collision along the Bohemian Massif margin. Sedimentation began in the Egerian/Eggenburgian due to transgression from the Eastern Alpine Foredeep (Molasse Zone). Maximum subsidence, caused by the weight of the nappe thrust stack and the deep subsurface load of the down-going plate, led to transgression from the Mediterranean area across the Pannonian back-arc basin, thus flooding the Carpathians. The Karpatian deposits have been studied in detail by Adámek et al. (2003). This period of sedimentation ended after the Lower Badenian, contemporaneously with cessation of the subduction and collision process in this part of the Western Carpathian orogen.

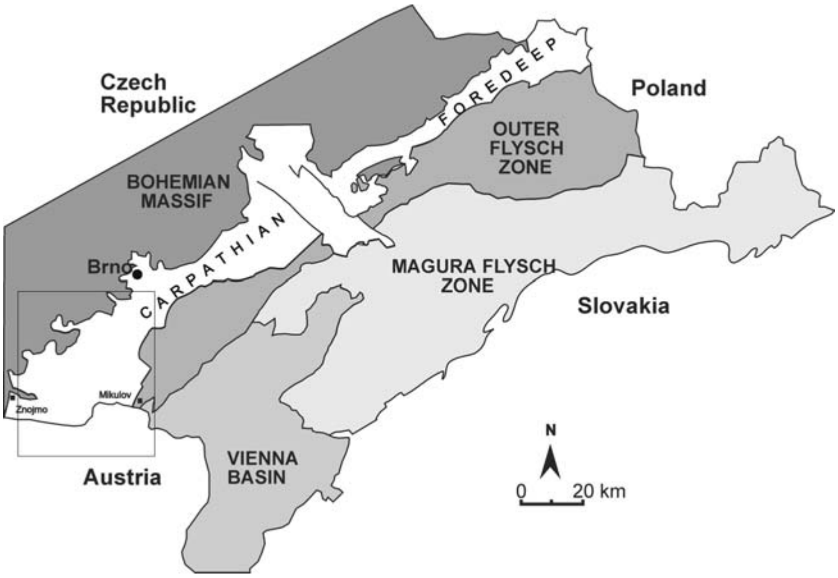

Figure 1. Location of the study area.

Methods and data

Well log data from the following boreholes were re-interpreted for this study: Brod 1; Březí 1; Dolní Dunajovice 1, 2, 3, 5, 13 (Dun1, 2, 3, 5, 13 in Figs 2, 4–8); Hrušovany 1 (Hru1 in Figs 2, 4–8); Iváň 1; Měnín 1 (Měn1 in Figs 2, 4–8); Mikulov 1, 2, 4 (Mik1, 2, 4 in Figs 2, 4–8); Mušov 1, 2, 3 (Muš1, 2, 3 in Figs 2, 4–8); Nesvačilka 1, 2, 3 (Nes1, 2, 3 in Figs 2, 4–8); Nikolčice 1, 3, 4, 5, 6, 7 (Nik1, 3, 4, 5, 6, 7 in Figs 2, 4–8); Nosislav 3 (Nos3 in Figs 2, 4–8); Novosedly 1 (Novos1 in Figs 2, 4–8); Nový Přerov 1, 2, 5 (N.Přerov1, 2, 5 in Figs 2, 4–8); Pasohlávky 1, 2G (Pasoh1, 2G in Figs 2, 4–8); Pohořelice 1, 3 (Poh1, 3 in Figs 2, 4–8); Pouzdřany 1 (Pouz1 in Figs 2, 4–8); Újezd 1. These boreholes are located mostly in the southern or south-eastern part of the Carpathian Foredeep (Fig. 2).

Data of differing quality were obtained from western edge of foredeep. This area had been explored mainly by hydrogeological boreholes, from which well log data were not collected in most cases. (HJ2 Otmarov (HJ2 in Figs 2, 4–8); HJ3 Žatčany (HJ3 in Figs 2, 4–8); HJ4 Syrovice (HJ4 in Figs 2, 4–8); HJ102 Syrovice (HJ102 in Figs 2, 4–8); HJ103 Opatovice (HJ103 in Figs 2, 4–8); HJ401 Troskotovice (HJ401 in Figs 2, 4–8); HJ402 Litobratřice (HJ402 in Figs 2, 4–8); HJ403 Hrabětice (HJ403 in Figs 2, 4–8); HJ404 Nová Ves (HJ404 in Figs 2, 4–8); HJ417 Pasohlávky (HJ417 in Figs 2, 4–8); HJ418 Drnholec (HJ418 in Figs 2, 4–8); HJ419 Drnholec (HJ419 in Figs 2, 4–8); HV102 Malešovice (HV102 in Figs 2, 4–8); HV103 Kubšice (HV103 in Figs 2, 4–8); HV104 Branišovice (HV104 in Figs 2, 4–8); HV105 Nová Ves (HV105 in Figs 2, 4–8); HV106 Moravské Knínice (HV106 in Figs 2, 4–8); HV107 Jiřice (HV107 in Figs 2, 4–8); HV108 Vlasatice (HV108 in Figs 2, 4–8); HV202 Damnice (HV202 in Figs 2, 4–8); PMK1A Suchohrdly (PMK1A in Figs 2, 4–8); PMK2 Miroslav (PMK2 in Figs 2, 4–8); PMK3 Našiměřice (PMK3 in Figs 2, 4–8); PMK3A Kubšice (PMK3A in Figs 2, 4–8); PMK4A Jezeřany (PMK4A in Figs 2, 4–8); PMK5 Olbramovice (PMK5 in Figs 2, 4–8); PMK5A Trboušany (PMK5A in Figs 2, 4–8); PMK6 Vedrovice (PMK9 in Figs 2, 4–8); PMK10 Maršovice (PMK10 in Figs 2, 4–8). However, these boreholes were fully cored, and we were able to use that relatively detailed stratigraphical documentation.

The following boreholes from the wider study area were also used: Artha H-2; Brno 1; Sokolnice 1 (Sok1 in Figs 2, 4–8); Cf600 Mušov 1 (/Cf600Muš1 in Figs 2, 4–8); Cf600 Mušov 2 (Cf600Muš2 in Figs 2, 4–8); Cf600 Mušov 3 (/Cf600Muš3 in Figs 2, 4–8); Cf600 Mušov 4 (Cf600Muš4 in Figs 2, 4–8); Cf600 Drnholec 4 (Cf600Drn4 in Figs 2, 4–8); Cf600 Drnholec 5 (Cf600Drn5 in Figs 2, 4–8); Cf600 Drnholec 7 (Cf600Drn7 in Figs 2, 4–8); Cf600 Drnholec 8 (Cf600Drn8 in Figs 2, 4–8); Cf600 Drnholec 9 (Cf600Drn9 in Figs 2, 4–8).

The study area of the present work is represented by boreholes in which well log measurements were taken throughout the twentieth century. Only the standard methods of well log measurements were used during that time (SP; Rag 2.12). Given the limited set of well log methods, we found it most advantageous to combine the measurement of ABK-3 resistance curves with gamma well log (GK) and neutron-gamma well log (NGK) measurements for dividing the lithofacies of the drillings. For older boreholes, we used the measurement of spontaneous polarization (SP) and resistance (Rag 2.12). These methods of well log measurement best grasp the overall lithological character of the layers.

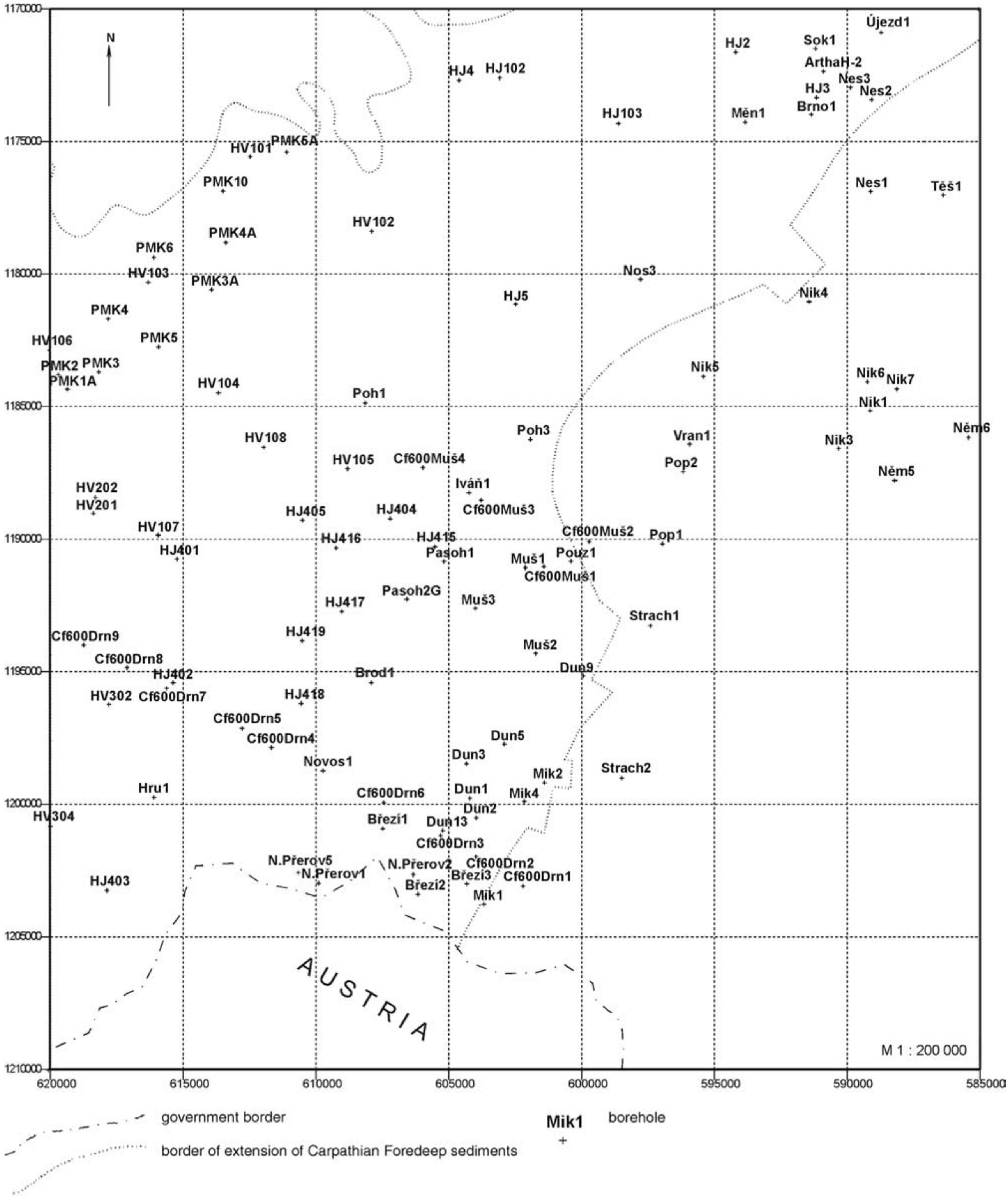

Figure 2. Area of interest.

Results

Identification of well log facies

Thirteen well log facies were identified based on the measuring of spontaneous polarization (SP) and resistance (Rag 2.12) in drill cores from the study area (Fig. 3). Each of these well log facies was alphabetically marked from A to O.

Well log facies A (Eggenburgian): Well log curves of this type have a dominantly block character and consist mainly of coarse-grained conglomerates, tabular sandstones, and clays.

Well log facies B (Eggenburgian): These well log curves have an uniform, smooth shape. Their sharp base

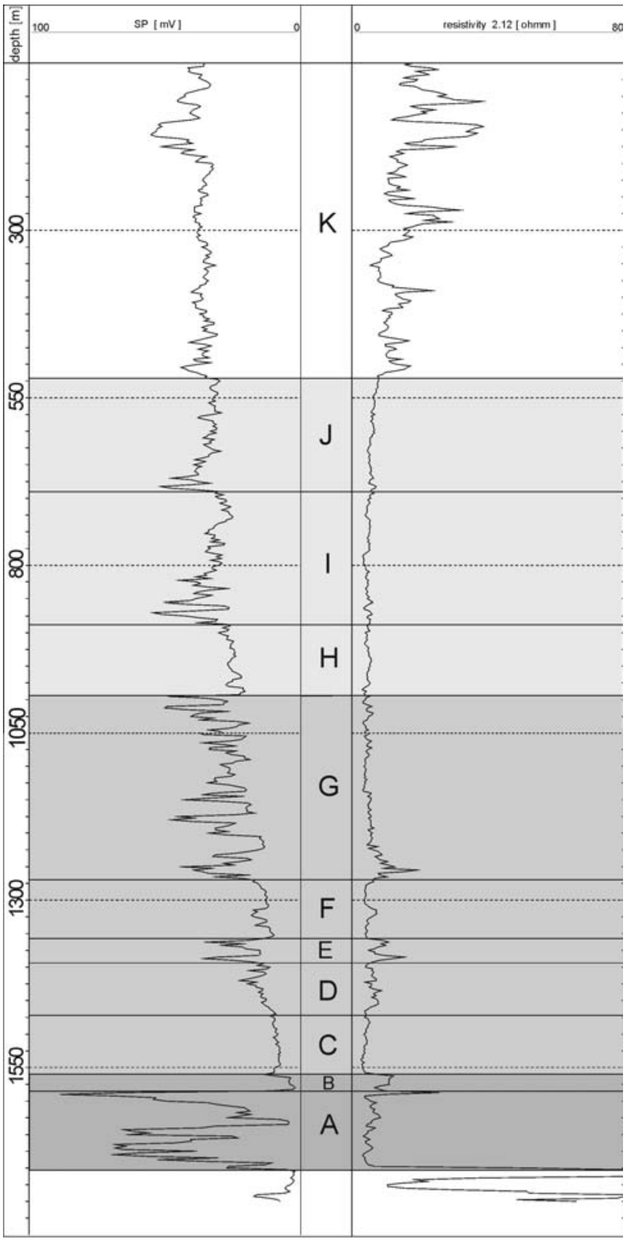

Figure 3. Interpreted well log facies in the borehole Mikulov 1.

corresponds to an increase of spontaneous potential values and a drop in resistivity values. Conversely, their upper boundary is characterized by a drop in spontaneous potential and resistivity Rag 2.12. These facies are predominantly of mudstones and claystones.

Well log facies C (Eggenburgian): The base is characterized by a drop in spontaneous potential and resistivity Rag 2.12. The curves of these log profiles have irregular shapes. The funnel shape is connected with an increase in grain-size towards the top, or with several small upward--coarsening cycles. These are interpreted as generally fine-grained deposits (claystones, mudstones, siltstones and fine sandstones) based on the wire-line logs.

Well log facies D (Karpatian): The typical funnel shape of this well log profile is interpreted as the result of deposition that coarsened upward, and corresponds to an increase in grain size, higher content of sandstone beds, or thicker bedding towards the top.

Well log facies E (Karpatian): This well log profile is characterized by a serrated bow shape with several small coarsening-upward cycles. Sandy claystones and the alternation of claystone beds with fine-grained sandstones and mudstones form the lithological content.

Well log facies F (Karpatian): This well log profile is irregular, with what appear to be several small cycles of upward coarsening. Claystones and mudstones strongly predominate these facies, with only laminae of fine-grained sandstone.

Well log facies G (Karpatian): This well log profile is very irregular, typified by frequent alternations between relatively higher and lower values of both spontaneous potential and resistivity Rag 2.12. Such shape is interpreted as the rhythmic alternation of fine-grained sandstones and mudstones. "Schlier" is typically present.

Well log facies H (Karpatian): This well log profile is irregular, and is also typified by frequent alternations between relatively higher and lower values of spontaneous potential and resistivity Rag 2.12. The lithology is predominantly comprised of "schlier" and alternating claystones and siltstones.

Well log facies I and J (Karpatian): These well log profiles are irregular, and sometimes bell-shaped, resulting in the gradual increase of spontaneous potential value and the decrease of resistivity.

Well log facies K (Karpatian): This well log profile is very irregular. The alternation of numerous upward coarsening (funnel shaped) and upward fining (bell shaped) cycles are apparent. The lithological content is highly variable, with a combination of fine grained (claystones, mudstones, siltstones) and coarse-grained (sandstones) deposits.

Well log facies O (Ottnangian) and L (Lower Badenian) were recognised very rarely in the studied boreholes and the low quality of the well log profiles makes their interpretation complicated.

Thickness maps of the well log facies

The selected well log facies may be used to characterize certain periods of the basin development. For this purpose, maps of the thicknesses of the well log facies were produced. These maps were created for groups of well log facies and for individual well log facies. Groups of well log facies were defined based on the thickness of the individual facies and their lateral extent, the lithology of the drill cores and their stratigraphical range. The well log facies maps cover a significant area of the southern part of the Carpathian Foredeep, with a small overlap of the central part.

The thickness map for well log facies A + B (Fig. 4) shows distinct elevations of the pre-Neogene basement, which generally stretch along the SSW-NNE direction. To the south is the Novosedly elevation (the area of the Nový Přerov 1, Nový Přerov 5, Novosedly 1, Březí 1, and Cf600-Drnholec 6 boreholes). Minor elevations developed within the locality of the Mušov 3 borehole and in the areas

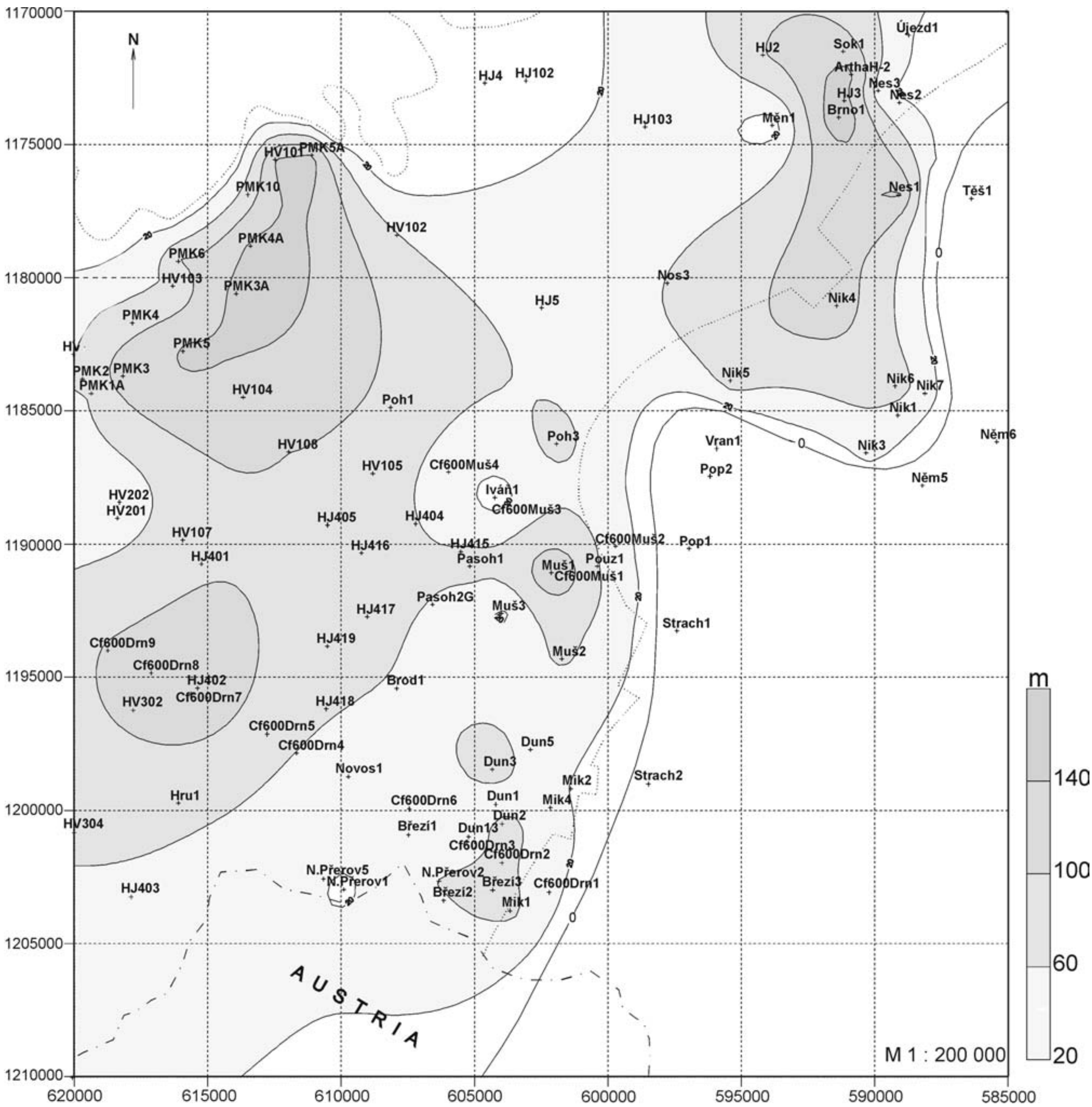

Figure 4. Map of thickness of well log facies A + B (Eggenburgian).

of Iváň 1 and Měnín 1 boreholes. Looking at the thickness map, one can identify several areas with greater thicknesses of well log facies A + B (with depocenters on the NW edge of the basin in the area of PMK boreholes, the east edge of the Mušov 1 borehole, and in the area of Nikolčice boreholes). The sedimentation can be regarded as early flexural: the sediment source on the passive edge played an important role, whereas that of the active edge (in the context of Carpathian Flysch belt) was relatively minor and was controlled by changes in the relative levels and rate of transport of sediment.

The thickness map of well log facies C + D + E + F (Fig. 5) indicates a very limited amount of sediments belonging to these facies. These deposits formed a rim along the active front of the Outer Carpathian nappes. The largest thicknesses were measured in the depocenter Mikulov 1, 2, 4, and Pouzdřany 1 boreholes. The second area showing distinct thicknesses of the sediments belonging to well log facies C + D + E + F is the depocenter of the Nikolčice 3, Nikolčice 5, Nikolčice 6, and Nikolčice 7 boreholes. Both depocenters are characterized by noticeably large thicknesses, which are considerably limited in area. An important question is whether these sediment thicknesses are primary or whether they were influenced by tectonic activity. The main subsidence was located at the active edge of the basin, where the sedimentation was of a relatively uniform fine-grained nature (Flemings and Jordan 1989). The distinct shapes of well log curves (Šikula and Nehyba 2003) that show an upwards-coarsening trend can be linked with cyclic sedimentation. These reflect transgressive-regres-

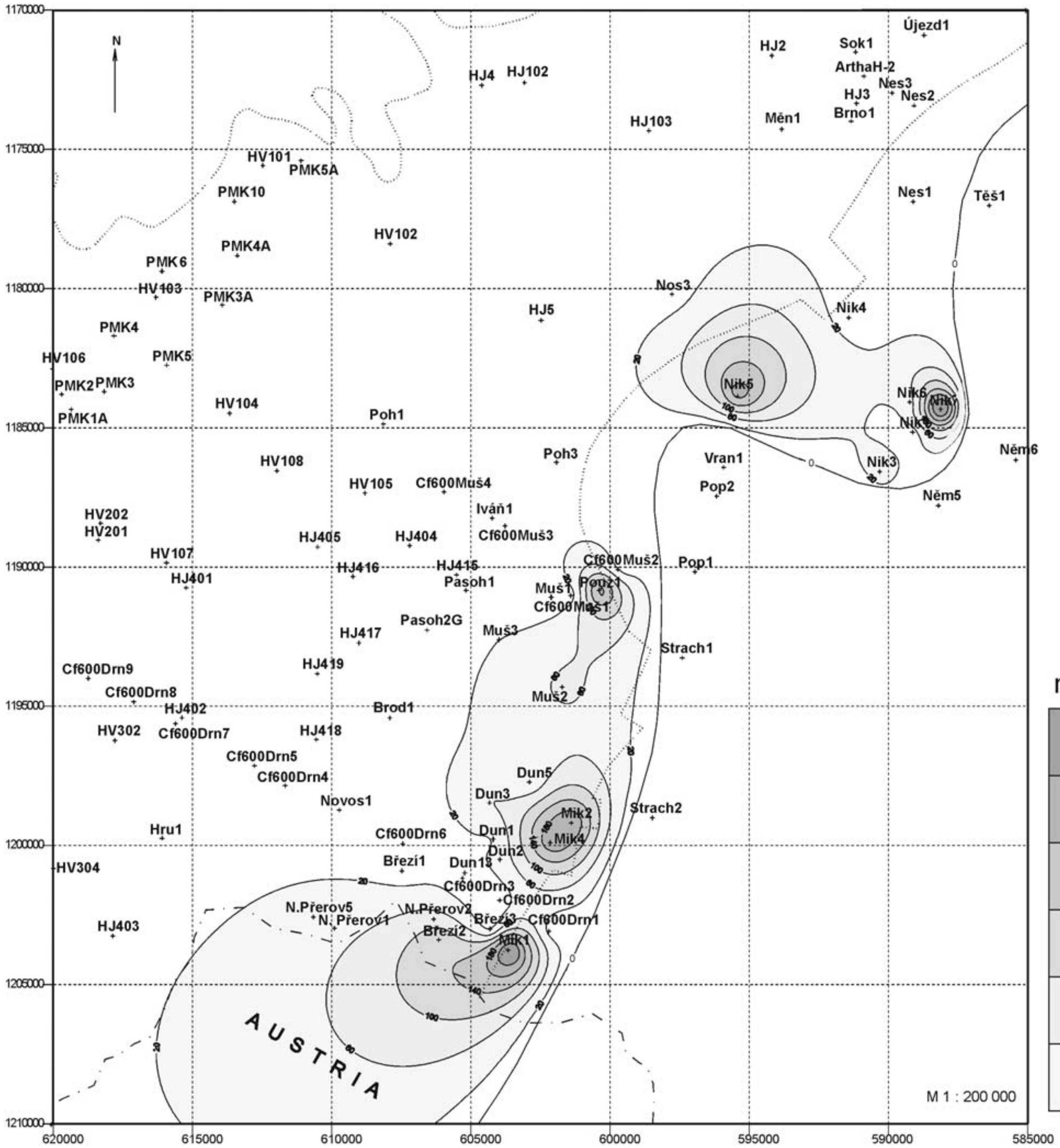

Figure 5. Map of thickness of well log facies C + D + E + F (Eggenburgian – Lower Karpatian).

sive cycles, presumably controlled by tectonic activity (i.e. by the movements within the nappe front). The sedimentation as a whole is of a distal nature.

The thickness map of well log facies G + H + I + J (Fig. 6) indicates the higher abundance of these facies than of well log facies C + D + E + F. Large thicknesses have evolved especially in the vicinity of the depocenters located in the areas of the Březí 3, Mikulov 1, Mikulov 2, and Mikulov 4 boreholes. These depocenters stretch along the nappe front in a NNE-SSW direction. The shapes of the sediment bodies of well log facies G + H + I + J and their lithology indicate that they belong to a clastic wedge, the deposition of which was to a large extent influenced by the processes occurring within the active edge of the basin.

The thickness map of well log facies K (Fig. 7) demonstrates that the sediments belonging to this facies cover almost the entire area of interest. Their zero-isoline in the west and north-west constitutes the contact with underlying sediments that range from Eggenburgian to Ottnangian. The map indicates a certain (generally westward) shift of the depocenters. The depocenters in the southern were located in the areas of the Nový Přerov 5, Nový Přerov 1, Březí 1 and Cf600 Drnholec 6, Mušov 3, and Mušov 1 boreholes. A minor depocenter is located to the north, in the vicinity of the Nosislav 3 borehole. These

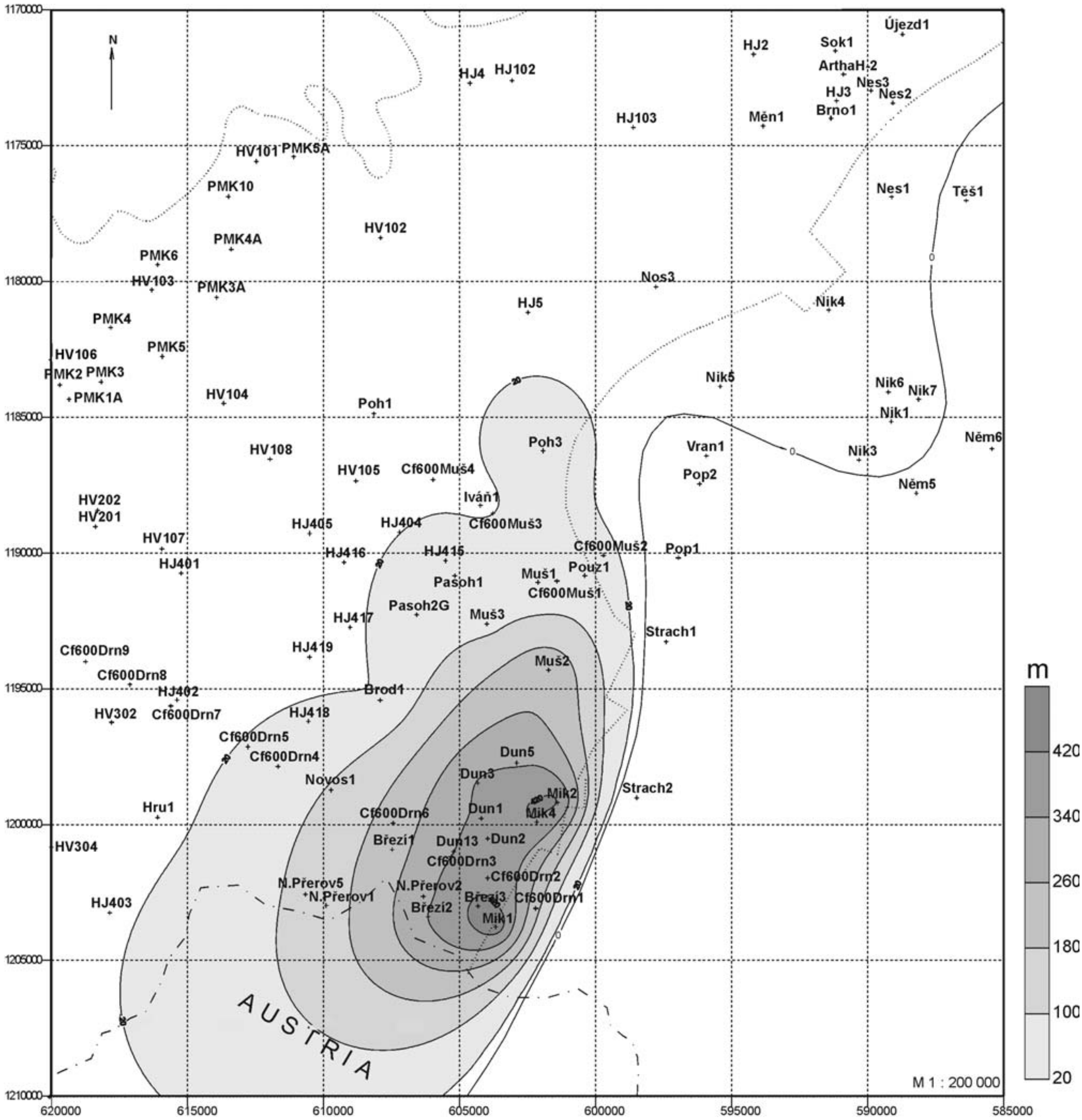

Figure 6. Map of thickness of well log facies G + H + I + J (Karpatian).

facies K depocenters are generally stretched along the thrust front in a SSW-NNE direction. One of the striking features of the thickness map of facies K is the presence of several subsurface elevations. The most distinct elevation lies in the vicinity of the Měnín 1 borehole. This elevation occurs in the very center of the Carpathian Foredeep, an area lacking well log facies A to K (i.e. Eggenburgian to Karpatian).

The map of well log facies L (Fig. 8) indicates that sediments occur in the central part of the basin, a certain distance from its active and passive edges. The sediments of facies L are in contact with the crystalline basement only at the basin margin, in the northern part of the study area (a transgressive contact). The noticeable linear definition of the basin itself, orientated in a SW-NE direction, resembles a trough-like structure. This feature, referred to by a number of authors as the central depression (see Eliáš and Pálenský 1998), corresponds to a basin formed during tectonic extension (Busby and Ingersoll 1995).

Interpretation

The Carpathian Foredeep sediments reflect several stages of basin evolution as well as the position of the Outer Carpathian front during collision with the European Platform.

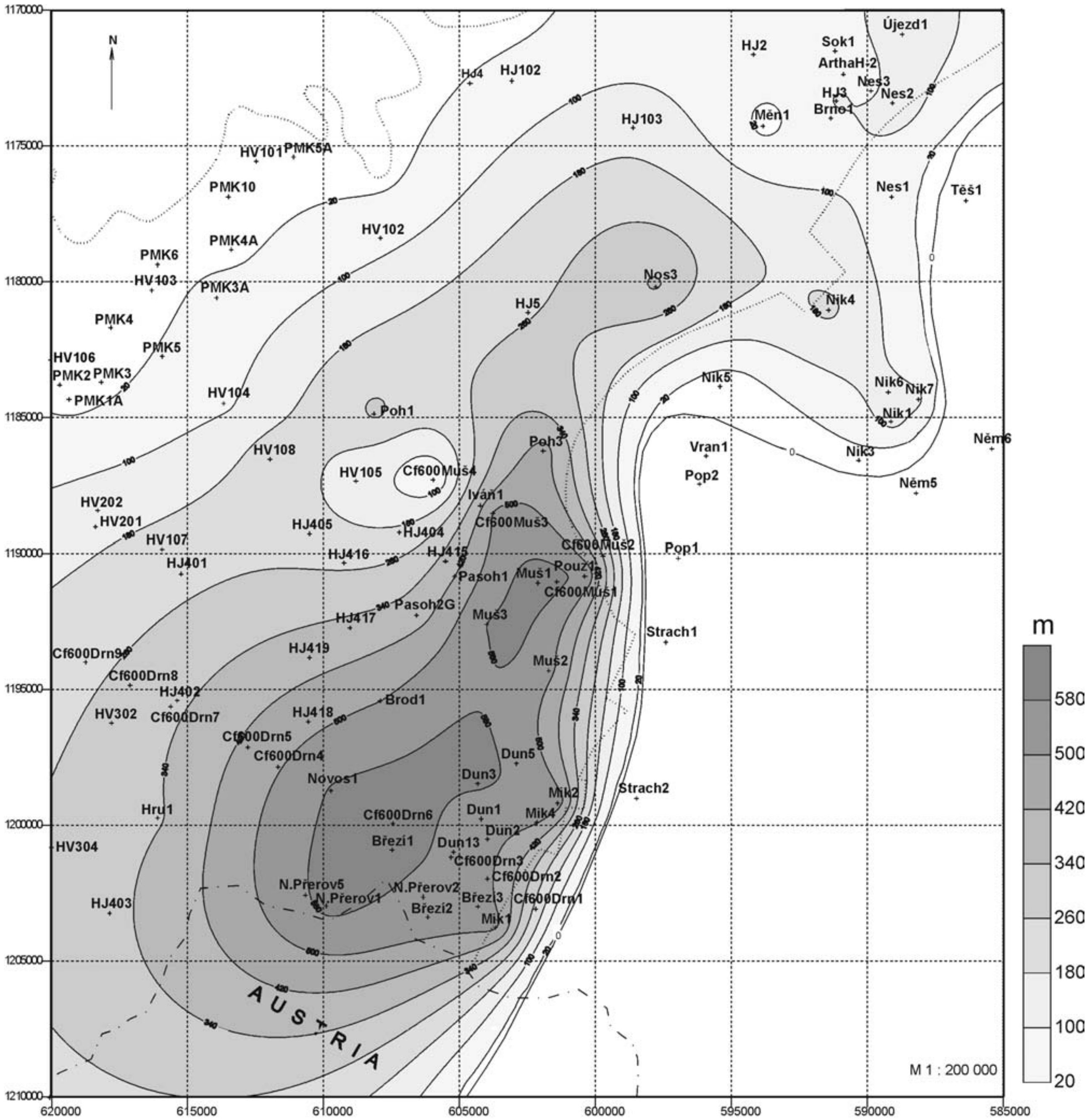

Figure 7. Map of thickness of well log facies K (Karpatian).

Each stage is represented by the characteristic depositional structures of the sedimentary deposits, reflecting the varying structural positions of the basin and the combination of predominant factors. Knowledge of the lithological composition and the spatial range of these well log facies allows to draw some conclusions about the development of the basin depocentres in time and space, the processes controlling sedimentation, and the basic structure of the basin. These stages can be followed in the thickness maps of the well log facies.

The first evolutionary stage of the southern part of the Carpathian Foredeep is represented by well log facies A and B (Eggenburgian). The main controlling factors were probably eustatic sea level changes, rate of sediment supply, and the character of the deposited material. The role of pre-Neogene basement relief was also important, whereas the influence of tectonic activity was rather general. The study area represents a peripheral part of the Alpine Foredeep.

The second stage (Eggenburgian–Lower Karpatian) of the basin development is represented by well log facies C, D, E, and F. The shape of the basin reflects deposition within the lower part of a synorogenic clastic wedge, and the formation of a typical peripheral foreland basin (Busby and Ingersoll 1995). The principal controlling factor of deposition and basin formation was thrust loading. The other factors, which included eustatic sea level

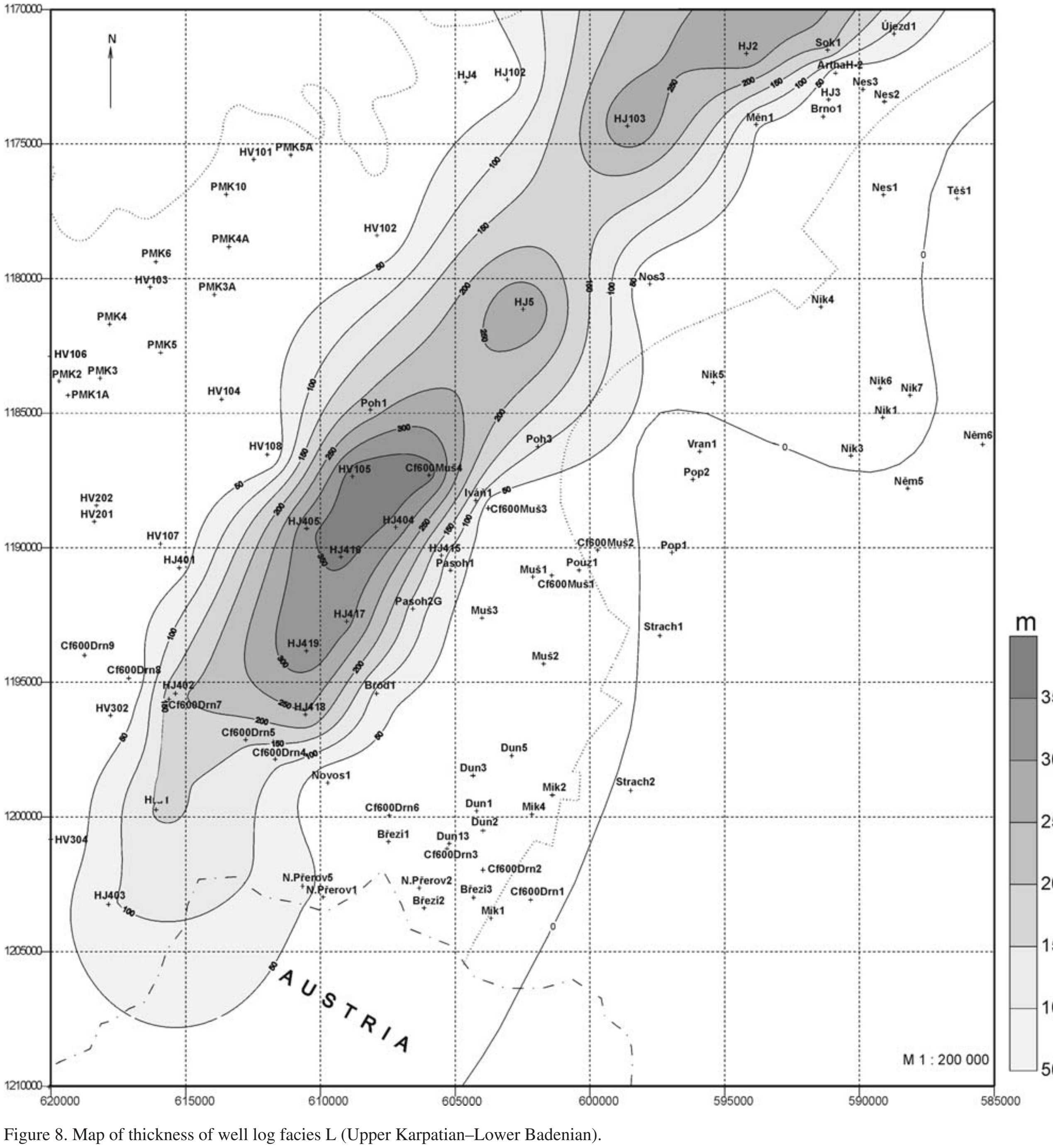

Figure 8. Map of thickness of well log facies L (Upper Karpatian–Lower Badenian).

changes and varying rates of deposition, played concomitant roles.

The third stage (Karpatian) of basin evolution is reflected by well log facies G, H, I, and J. The deposition of these facies is connected with synorogenic clastic wedge development. This stage was controlled mainly by the interaction between tectonic subsidence due to thrust loading and the isostatic rebound of the foreland.

The fourth stage (Karpatian) of the basin evolution is represented by well log facies K. This facies is connected with synorogenic clastic wedge development, which was controlled mainly by tectonic activity. Other factors were also important, especially the rise in sea level during the global sea level change of the TB 2.2 cycle (sensu Haq et al. 1988, Haq 1991). The combination of the tectonic activity and the rise in sea level encouraged transgression and thus increased the extent of the Karpatian flooding in all Western Carpathian Neogene basins (Kováč 2000, Kováč et al. 2001).

The fifth stage (Upper Karpatian–Lower Badenian) is represented by well log facies L. This facies represents sedimentation in a basin opening in transtensive mode. The depositional area formed within the basin fill itself, under the influence of stress fields associated with the collision front.

In addition to peicing together the basin structure, the present study has also compiled a lithostratigraphic data-base of the basin. Attention was given to the stratigraphic position of the selected well log facies. This approach was chosen with regard to the basin development, the thickness of individual well log facies, and their stratigraphic range. Such division of the well log facies provides a suitable basis for lithostratigraphy. Subsequently, the individual well log facies or their groups may, after the necessary formalisation, form the basis of lithostratigraphical units. The recognition of the cyclical character of the sedimentation and its controlling factors provides a basis for further sequence stratigraphy studies.

Conclusion

Thirteen well log facies were identified in the southern part of the Carpathian Foredeep based on reinterpreting measurements of spontaneous polarization (SP) and resistance (Rag 2.12), and the lithological study of drill cores. The selected well log facies are used for characterising the basin structure during its development. Maps of the thicknesses of the well log facies were produced. These maps allow to illustrate five stages of basin development. Individual stages also reflect the controlling factors of basin and depositional space formation.

The first stage (Eggenburgian) reflects the situation of the most distant part of the Alpine Foredeep, in which the main controlling factors were changes in eustatic sea level (sensu Haq et al. 1988, Haq 1991), rate of sediment supply, character of the deposited material, and basement relief. A typical peripheral foreland basin was formed during the second stage (Eggenburgian–Lower Karpatian), with the deposition of a synorogenic clastic wedge. The principal factor influencing deposition and basin formation at this stage was thrust loading. This situation continued during the subsequent two stages (Karpatian) under the combined influence of tectonic activity, isostatic rebound, and sea level change. During the fifth stage (Upper Karpatian–Lower Badenian) basin formation and deposition were connected with a transtensive stress field.

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