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The Neogene Styrian Basin: An overview

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ABSTRACT

The more than 4 km deep Styrian Basin is located at the eastern margin of the Alps and forms part of the Pannonian Basin System. It represents an extensional structure on top of a crustal wedge, which moved eastward during the final stages of the Alpine orogeny.

Basin evolution can be subdivided into an early Miocene (Ottnangian to Karpatian) synrift and a middle to late Miocene postrift phase of subsidence. During the synrift phase thick clastic limnic/fluviatile and marine sediments were deposited. The climax of extension during the synrift phase favoured the ascent of andesitic magmas. Sedimentation during the postrift stage is controlled by middle Miocene transgressions and a subsequent regression with a lowering of salinity. During this time period intercalations of sandy and shaly sediments and algal reefs were deposited. In Pliocene times a basin inversion resulted in the erosion of a few hundred meters of sediment. Uplift was accompanied by a second volcanic phase producing basalts in Plio-/Pleistocene times.

The heat flow evolution of the Styrian Basin was governed primarily by the Miocene magmatic event. Volcanic centers were characterized by extremely elevated heat flows (>300 mW/m^2) and heat flow decreased to background values (about 120 mW/m^2) at a distance of about 10 kilometers from the centers. After the early Badenian heat flows decreased and are in the range of 55 to 85 mW/m^2 since Sarmatian times. A second volcanic phase in Plio-/Pleistocene times had only minor influence on the regional heat flow pattern.

Subsidence analysis and the results of quantitative basin modelling suggest that the lithosphere beneath the Styrian Basin was extremely weak during Ottnangian/Karpatian times, probably caused by high extension rates and high heat flows. Subsequent cooling lead to a pronounced increase in flexural rigidity. Depth dependant rheology models based on paleo-heat flow estimates indicate a similar increase in lithospheric strength with time. The impact of Plio-/Pleistocene volcanism on rheology appears to be relatively modest, which can be explained by a deep position of the magma chamber for this event.

Key words: Styrian Basin, Miocene, subsidence, basin modelling, rheology

Introduction

The Neogene Styrian Basin, situated at the eastern margin of the Eastern Alps, is a subbasin of the Pannonian Basin System (Fig. 1). It is about 100 km long and 60 km wide. The South Burgenland Swell separates the Styrian Basin from other Neogene basins of the Pannonian realm. The Middle Styrian Swell separates the shallow Western from the deeper Eastern Styrian Basin. The Gnas, Fürstenfeld and Mureck Basins are distinct depocentres within the Eastern Styrian Basin. Miocene (Karpatian and Early Badenian) volcanics built up huge shield volcanoes. A second, basaltic volcanic phase occurred in Plio-/Pleistocene times (Fig. 1).

Despite of more than 20 deep boreholes, seismic data and magnetic and gravimetric maps (Kröll et al., 1988), the basement structure is not yet fully understood. This is partly due to the presence of several hundred meter thick Miocene volcanic rocks. Gravimetric models and new seismic interpretations (Sachsenhofer et al., 1996a) indicate that the top of the pre-Tertiary basement in both, the Fürstenfeld (3.7 km below sea level; s.l.) and the Gnas Basin (more than 4 km below s.l.) is considerably deeper than thought previously.

The aim of this paper is to summarize the most important results of an integrated basin analysis, including the geological evolution (Ebner and Sachsenhofer, 1995; Sachsenhofer et al. 1996a), thermal history (Sachsenhofer, 1994), and the results of quantitative tectonic models (Sachsenhofer et al., 1996b).

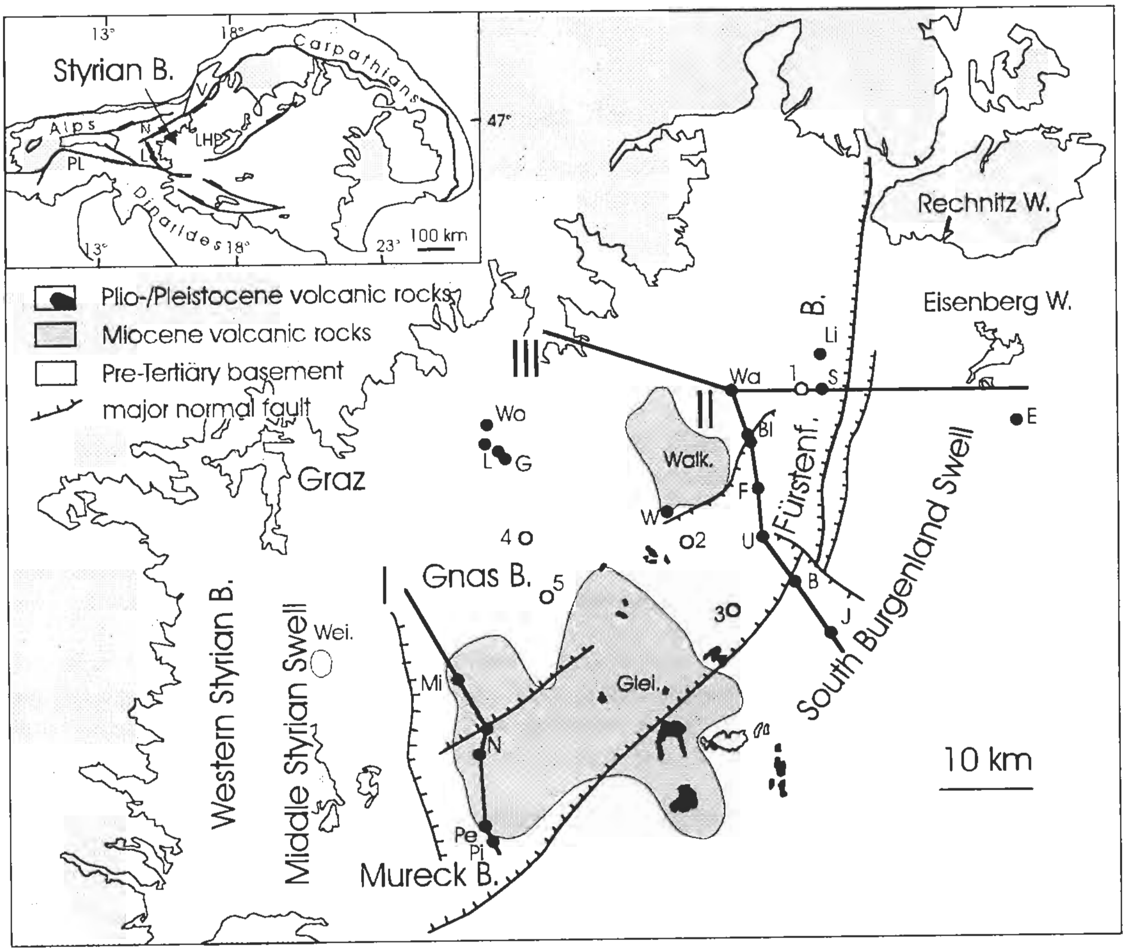

Fig. 1. Location of study area within the Pannonian Basin System and sketch map of the Styrian Basin. Legend: V: Vienna Basin, LHP: Little Hungarian Plain, PL: Periadriatic Lineament, N: Noric Depression, L: Lavant Line. I, II and III are cross-sections discussed in the text. Miocene volcanic complexes: Glei.: Gleichenberg; Walk.: Walkersdorf; Wei.: Weitendorf. Wells: Pi: Pichla 1; Pe: Perbersdorf 1; N: St. Nikolai 1, 2; Mi: Mitterlabill 1; G: Gleisdorf 1; L: Ludersdorf 1, 2; Wo: Wollsdorf 1; W: Walkersdorf 1; J: Jennersdorf 1; B: Binderberg 1; U: Übersbach 1; F: Fürstenfeld 1; Bl: Blumau 1, 1a; Wa: Waltersdorf 1; S: Stegersbach 1; Li: Litzelsdorf 1; E: Edlitz 1. 1, 2, 3, 4 and 5 are pseudo-wells.

Position of the Styrian Basin within the Alpine-Carpathian-Pannonian realm

The Styrian Basin developed in the transition zone between the Eastern Alps and the Pannonian realm. It is underlain by very low- to high grade-metamorphic rocks of the Austroalpine nappe system. Low-grade metamorphic Mesozoic rocks of the Penninic unit occur in the vicinity of the Rechnitz Window (Kröll et al., 1988).

The structure of the lithosphere beneath the Styrian Basin (e.g. Horvath, 1993; Lillie et al., 1994) emphasizes its position in the transition zone between the Eastern Alps and the Pannonian Basin System. The lithosphere is about 100 km thick (Aric et al., 1989). Xenoliths from 50 to 80 km depth (Kurat et al., 1980) give evidence for a brittleveined upper mantle (Vaselli et al., 1996), which is, however, less tectonized compared to the upper mantle beneath the central Pannonian region (Kurat et al., 1991). The crustal thickness beneath the Eastern Styrian Basin is about 30 km and decreases to 27 km in the western Little Hungarian Plain (Aric et al., 1987). A significant westward increase in crustal thickness is observed beneath the Western Styrian Basin (Walach and Weber, 1987). Whereas Aric (1981) suggested that especially the lower crust is thinned beneath the eastern termination of the Alps, Tari (1994) speculated on a pronounced local thickenning of the lower crust in the Rechnitz area. Balla (1994) postulated intra-crustal high-density bodies beneath the Eastern Styrian Basin and the Little Hungarian Plain.

The evolution of the basin is closely related to the late Alpidic geodynamics of the Alpine-Carpathian-Pannonian realm. Final compression across the Eastern Alps in Late Oligocene and Miocene times was accomodated by lateral extrusion of crustal wedges towards the Pannonian region along sets of major strike-slip faults (Genser and Neubauer 1989, Neubauer and Genser 1990, Ratschbacher et al. 1991). These movements initiated block rotations in the Pannonian realm and overthrusting in the outer Carpathians (Balla 1985, Royden 1988; Horvath, 1993; Mauritsch and Marton, 1995). Pull-apart basins formed in zones of major strike-slip faulting (e.g. Noric Depression, Vienna Basin; Fig. 1).

However, extension also occurred within the eastward moving crustal wedges. This caused subsidence in the Styrian Basin (Ebner and Sachsenhofer, 1991, 1995; Ratschbacher et al. 1991) and contemporaneous uplift of the Penninic Rechnitz and Eisenberg Windows (Dunkl and Demeny, 1996). Pull-apart mechanisms, initiated by the northward move of the Pannonian plate and the relative standstill of the Alpine orogenic front may have also played a role in the formation of the basin.

Tari (1994) introduced the term "Rába river extensional corridor" for this region, which includes the Styrian Basin and the Little Hungarian Plain. Following the terminology of Buck (1991), he proposed a temporal progression of extensional style: (1) a Karpatian core complex style extension, which resulted in the formation of the Penninic windows, (2) a Badenian wide-rift style extension and (3) a Sarmatian to lowermost Pannonian narrow-rift style extension, which was restricted to the Little Hungarian Plain.

Geologic evolution

The geologic history of the Styrian Basin is discussed in chronological order. The presentation is based on palaeogeographic maps of Ebner and Sachsenhofer (1995; Fig. 2), backstripped and modelled tectonic subsidence curves (Sachsenhofer et al., 1996b; Fig. 3), sketch maps showing modelled crustal and subcrustal stretching values (Sachsenhofer et al., 1996b; Fig. 4), and two cross-sections providing information on the heat flow evolution (Sachsenhofer 1994; Fig. 5). Rheological strength profiles (Sachsenhofer et al., 1996b; Fig. 6) and the results from quantitative flexural models along a W-E cross-section through the northern Fürstenfeld Basin (Fig. 7) are used to estimate lithospheric strength.

Ottnangian

Sedimentation in the central Eastern Styrian Basin started during Ottnangian time (Fig. 2a) with the deposition of basement breccias, red soils and thin coal seams, followed by shales, bituminous marls and coaly layers (Kollmann 1965). They are interpreted as flood plain and lacustrine swamp deposits. In the western Gnas Basin the thickness of Ottnangian sediments may reach 1,000 m. Sedimentation in this area probably took place under shallow marine conditions. The southern Western Styrian Basin was characterized by a coal-bearing fan delta complex in a fault-controlled setting. Stingl (1994) postulated a brackish to marine depositional environment for the upper part of the 2,000 to ?3,000 m thick sequence. Similar clastic sediments but without major coal seams occur also in the Mureck area. In the northern Western Styrian Basin up to 70 m thick coal seams were deposited during Ottnangian and/or early Karpatian times (Daxner-Höck et al., 1996).

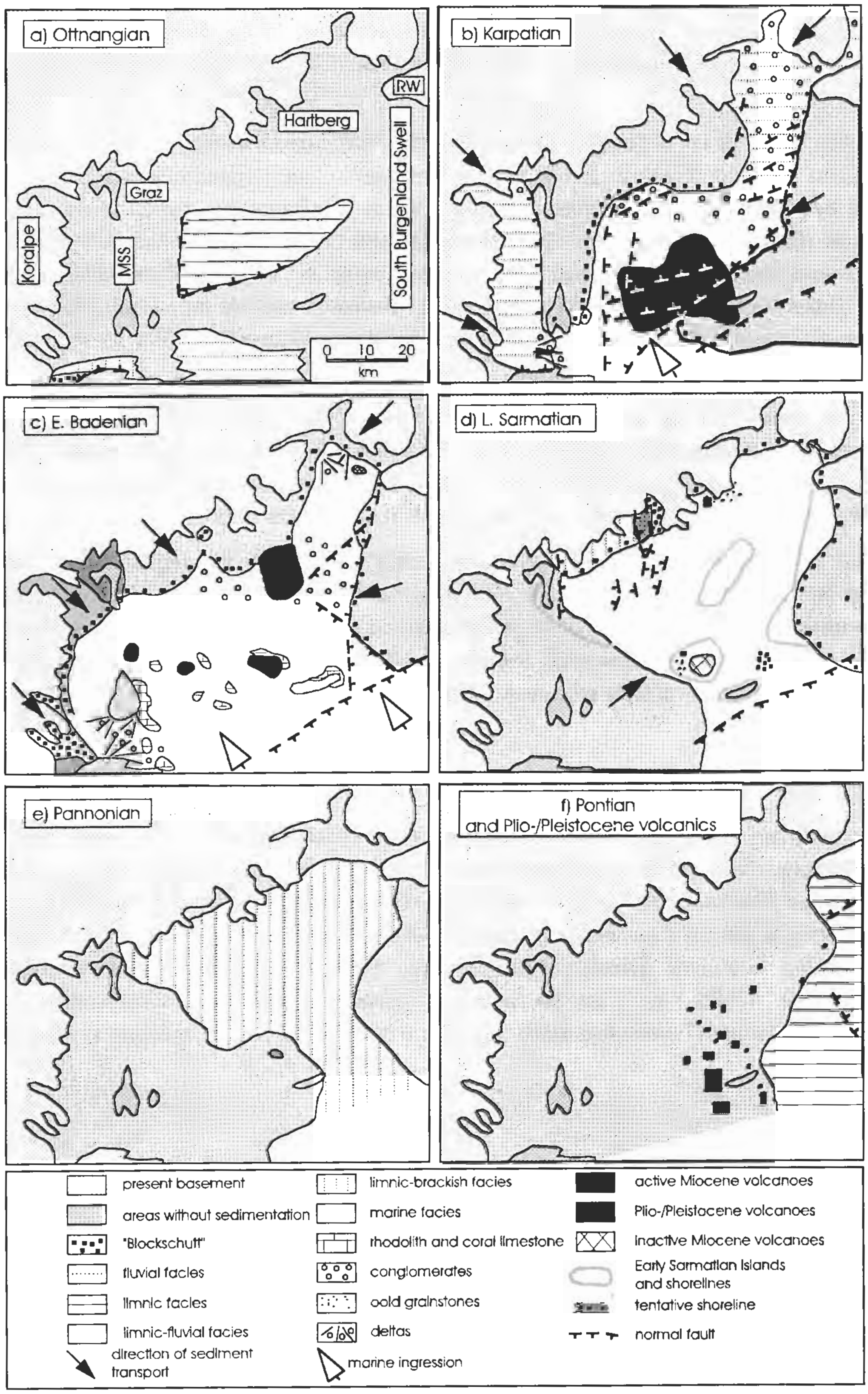

Fig. 2. Paleogeographic maps of the Styrian Basin: MSS: Middle Styrian Swell; RW: Rechnitz Window (Ebner and Sachsenhofer, 1995).

Karpatian

Extension increased during Karpatian time resulting in significant synsedimentary fault tectonics (Fig. 2b). Main Karpatian normal faults are orientated N-S (eastern margin of the Fürstenfeld Basin, western margin of the Gnas Basin) to NE-SW (southern Fürstenfeld Basin, southern Gnas Basin). Strong crustal and subcrustal stretching (modelled extension values are up to 1.3 [30 % extension] and 1.6 respectively; Fig. 4a,b) caused high syn-rift subsidence rates (Fig. 3) and a marine ingression. Rapid subsidence in the Gnas and Mureck Basins created deep-sea environments with a water depth of more than 500 m. There, several hundred metre thick calcareous mudstones and siltstones (Steirischer Schlier) were deposited. The northern part of the Fürstenfeld Basin and the Western Styrian Basin were subjected to a strong fluvial input of coarse clastic sediments and, therefore, managed to stay in a coastal environment. Towards the end of the Karpatian a major regression led to a wide-spread progradation of fans towards the basin centre.

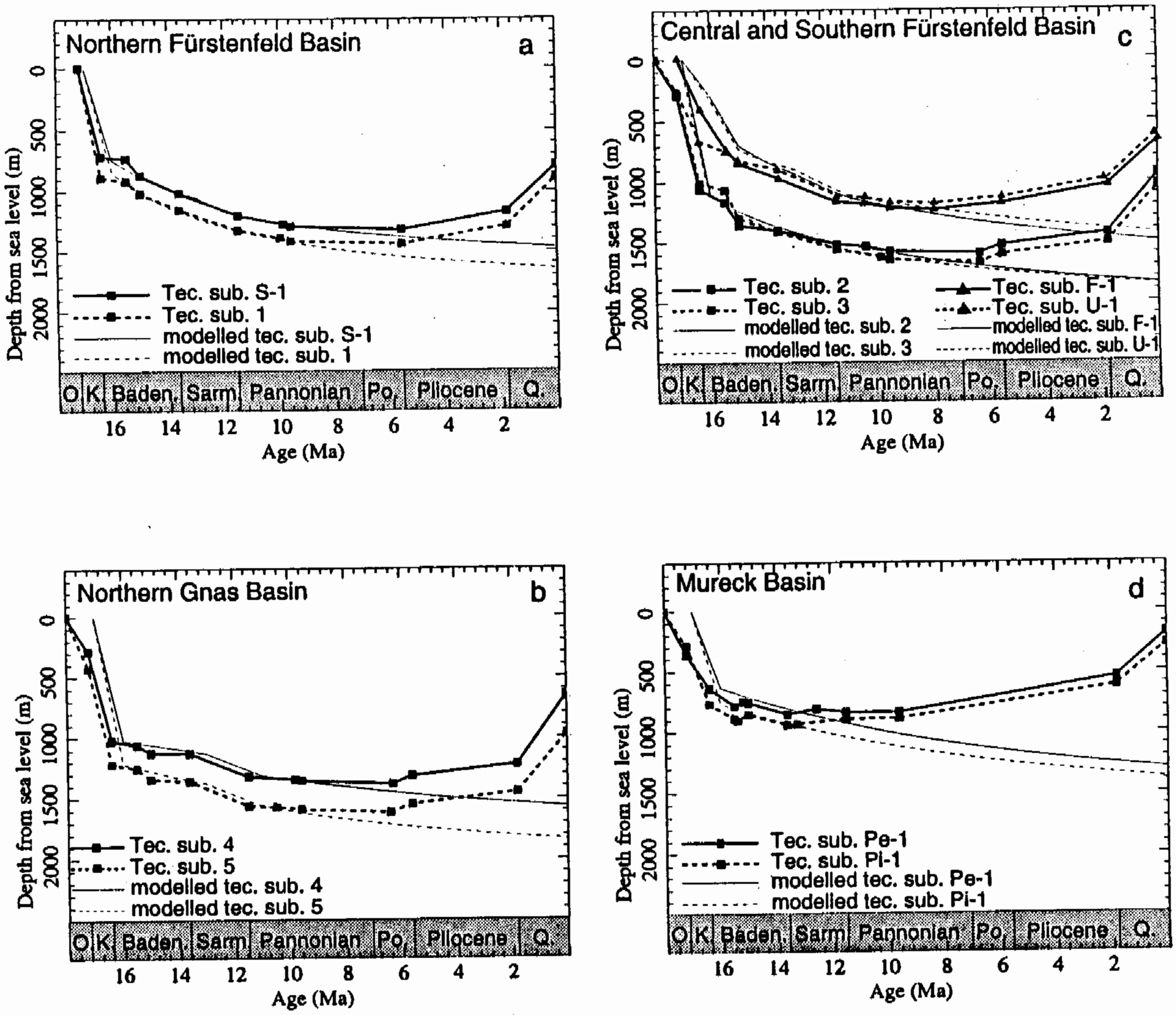

Fig. 3. Observed (backstripped) and predicted tectonic subsidence for some typical wells in the Styrian Basin, illustrating the effect of multiple extension phases and the amounts of post- and synrift subsidence (Sachsenhofer et al., 1996b). In the modelling of the basin history uplift was not taken into account. See Fig. 1 for location of wells. a. Backstripped and predicted tectonic subsidence for S-1 and pseudo-well 1. b. Backstripped and predicted tectonic subsidence for the pseudo-wells 4 and 5. c. Backstripped and predicted tectonic subsidence for F-1 and U-1 and pseudo-wells 2 and 3. d. Backstripped and predicted tectonic subsidence for Pi-1 and Pe-1.

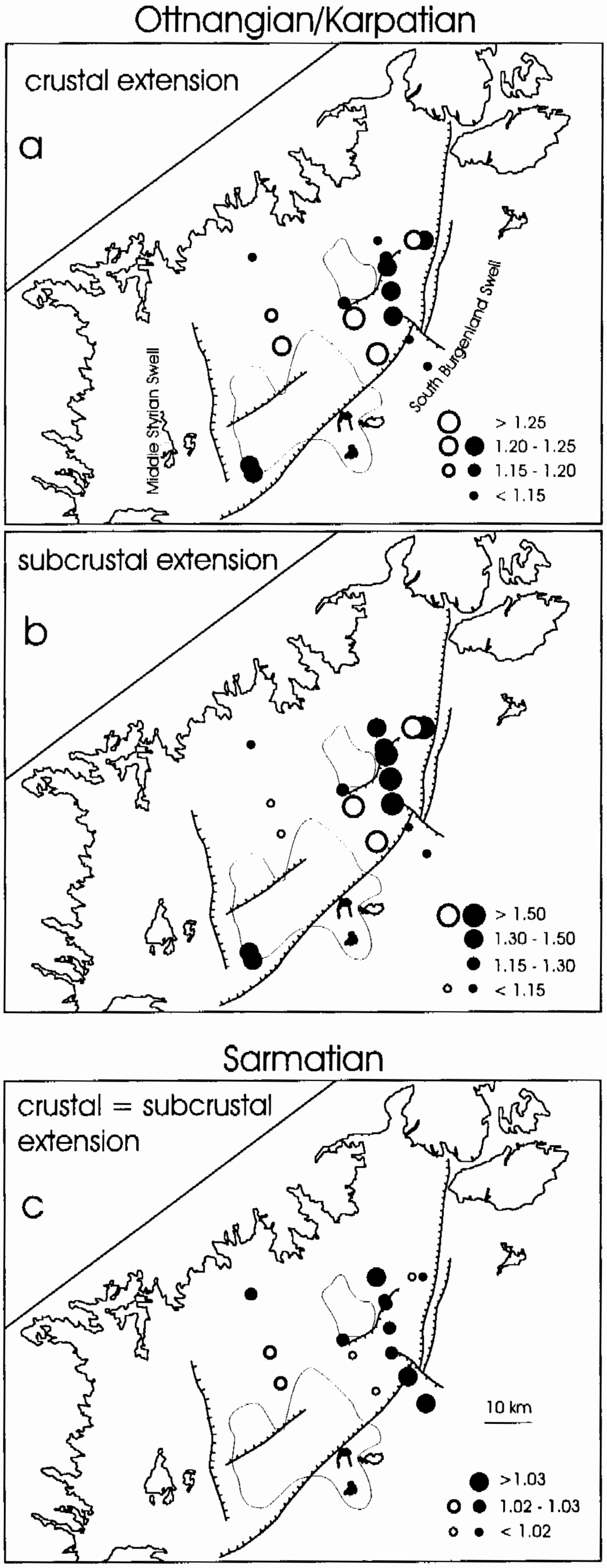

Fig. 4. Sketch map showing modelled extension values for the wells (full circles) and pseudo-wells (open circels) indicated in the map, using an isostatical approach (original crustal thickness: 45 km, original lithospheric thickness: 160 km). An extension value of 1.2 corresponds to 20 % extension (Sachsenhofer et al., 1996b). a. Crustal extension values for the Karpatian extension phase. b. Subcrustal extension values for the Karpatian extension phase. c. Lithospheric extension values for the Sarmatian extension phase (crustal and subcrustal extension values are modelled similar).

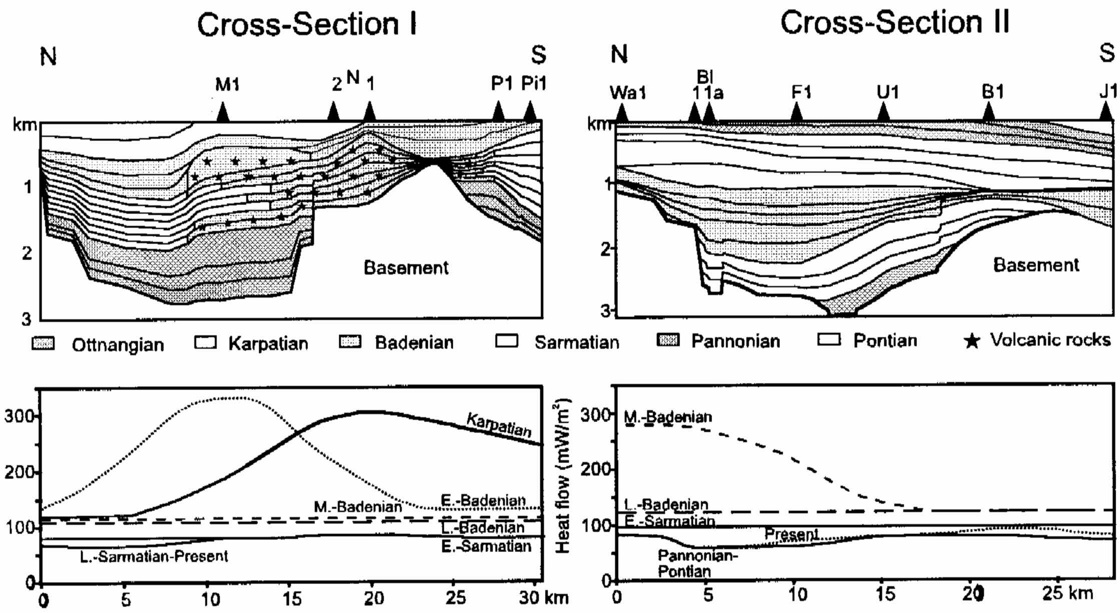

Fig. 5. Stratigraphy and heat flow evolution along cross-sections "I" and "II" (see Fig. 1 for position of cross-sections and abbreviatioin of wells; Sachsenhofer, 1994).

Synchronously with the extreme subsidence rates, volcanic activity started in the Styrian Basin and built up huge shield volcanoes, situated in the southern part of the Eastern Styrian Basin (e.g. Nikolai area; cross-section I; Figs. 2b, 5). As a consequence of shallow magma chambers, heat flow was extremely raised in the vicinity of the volcanic centers and decreased to - probably high - background values (120 mW/m^2) at a distance of about 10 km (Fig. 5). Evidence for high heat flow in the Rechnitz Window area is provided by coalification (Belocky et al., 1991) and fission-track data (Dunkl, 1992).

High heat flows and high extension rates caused a nearly completely loss of strength within the lithosphere (Fig. 6c,d) and a reduction of its effective elastic thickness (EET, cf. Banda and Cloetingh, 1992; Burov and Diament, 1995). Probably EET was smaller than 2 km. The postulated loss of strength within the lithosphere allowed the rapid contemporaneous uplift of the Penninic windows at the eastern end of the Alps (Fig. 7a-c) and is in agreement with Tari's (1994) ideas about lower crustal flow in the Rechnitz area.

The climax of tectonic movements occurred during latest Karpatian time (Friebe, 1991) forming Stille's (1924) "Styrian phase". These tectonic movements caused tilting of crustal blocks and uplift of the western hinterland, as well as uplift of the Middle Styrian Swell. There is strong evidence for major erosion (100 m?) along the basin margins. However, it is not clear whether the whole basin was emergent during this period.

Badenian

Although subsidence rates decreased significantly, and syn-rift subsidence may have continued only locally into early Badenian times (central Fürstenfeld Basin; Fig. 3c), the sea reached its largest extent at the end of the early Badenian (Fig. 2c).

Sedimentation started with coarse clastic sediments, which were deposited over the ("Styrian") unconformity. Coral reefs and rhodolithic platforms (Friebe, 1990, 1993) developed at different stratigraphic levels along the margins of the Middle Styrian Swell, at the northern margin of the Gnas Basin, and at the slopes of volcanic islands. In the central Eastern Styrian Basin a deep water environment with turbidites prevailed, while a siliciclastic lagoonal environment evolved in the Western Styrian Basin.

Whereas deep marine conditions persisted until Middle Badenian time, Late Badenian sediments were deposited in a shallow marine environment. A sea level fall at the Badenian/Sarmatian boundary caused a minor unconformity in the Eastern Styrian Basin as well as the progradation of fluvial and deltaic complexes in the northwestern Styrian Basin (Friebe, 1990). Erosion occurred mainly at the basin rims, but a slight unconformity can also be identified on some seismic lines in the central basin.

Magmatic activity continued until the end of the early Badenian and shifted northward. New volcanic complexes with shoshonitic and andesitic compositions were formed at Weitendorf and Walkersdorf/Ilz (Fig. 1), whereas the southern parts of the Karpatian volcanic islands were already buried by lower Badenian sediments (Fig. 5). In conformity with magmatic activity, the heat flow maxima shifted northward; e.g. to the Mitterlabill area, which became a center of volcanic activity during the early Badenian (Fig. 5). Whereas heat flow decreased immediately after the end of magmatic activity along cross-section I, it decreased only 1 million years after the end of magmatic activity along the northern part of cross-section II, situated close to the Walkersdorf/Ilz volcano (Figs. 1, 5). This indicates the presence of a larger magma chamber, which needed longer time for cooling.

The geodynamic setting of the Karpatian/early Badenian magmatism is still under debate. Ebner and Sachsenhofer (1991, 1995) speculated on the subduction-related origin of the K-rich subalkaline-alkaline magmas emphasizing the association of K-rich volcanics with areas of intense extensional and strike-slip tectonics during or after subduction processes (cf. Lange and Carmichael 1991). Trace element analysis of the Gleichenberg volcano, suggesting a magma derived from a mantle source and a subducted sedimentary component (Harangi et al., 1995) may support this hypothesis. Tari (1994) and Tari and Horvath (1995) proposed melting of crustal rocks due to rise and decompression of lower crustal material underneath the Rechnitz core complex.

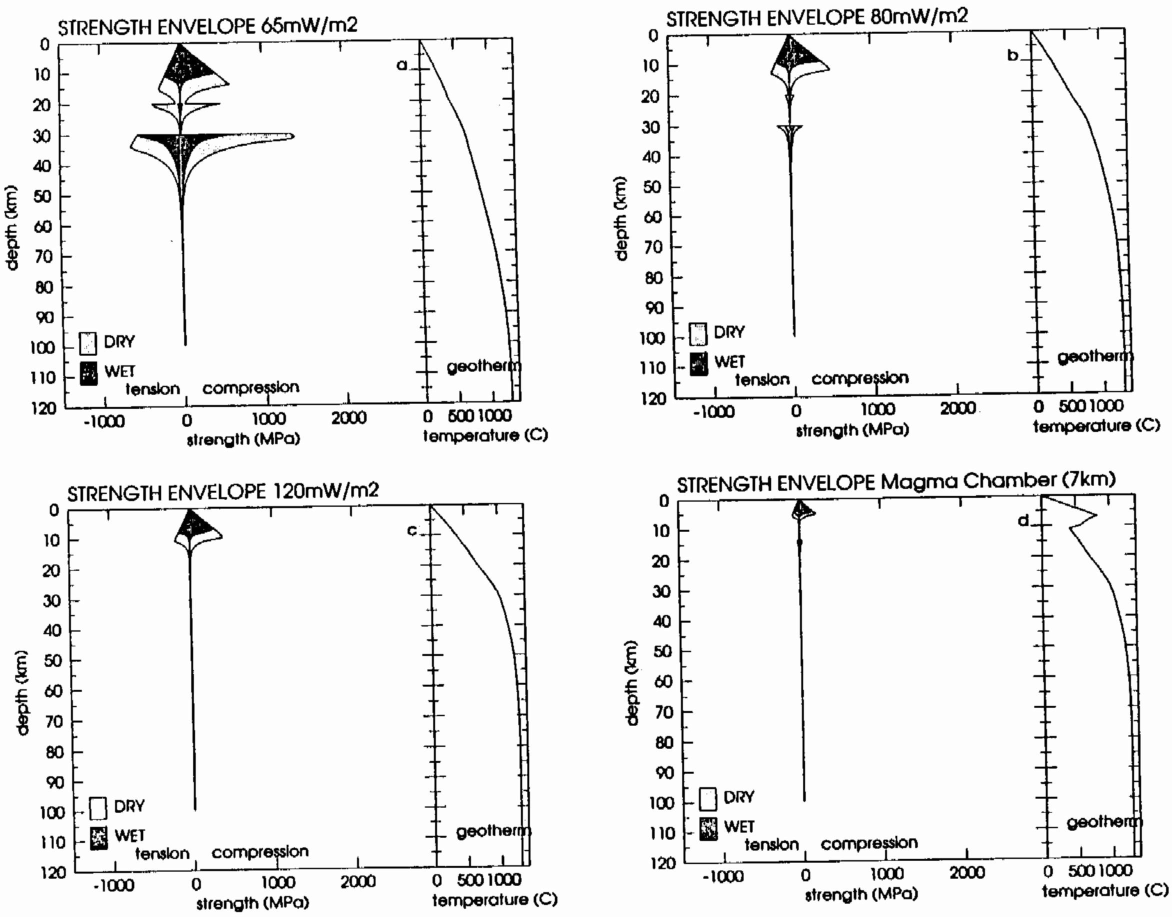

Fig. 6. The dependence of rheological strength profiles on heat flow. Models for the Styrian Basin (Sachsenhofer et al., 1996b).

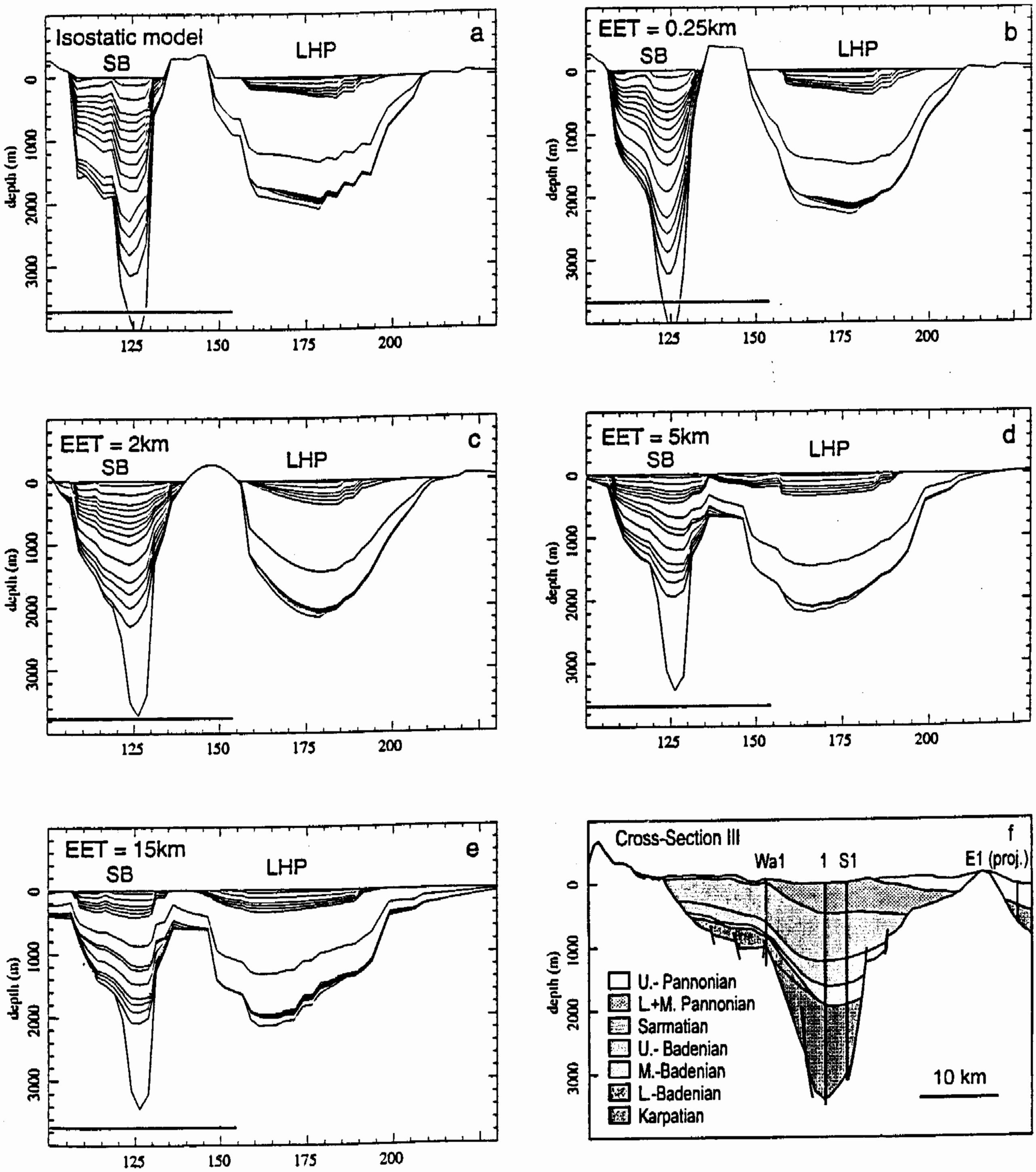

Fig. 7. Predicted stratigraphy for different EETs for a section through the northern Fürstenfeld Basin and the adjacent Little Hungarian Plain. Position of cross-section "III" (Fig. 7f) is indicated by a black bar. The model resolution is 1 Ma between 17 and 5 Ma and 2 Ma between 5 and 1 Ma. The model extends approximately 100 km outside of the basin area to correctly handle lateral heat conduction and flexure. For pre-rift crustal thickness of 45 km and pre-rift lithospheric thickness of 160 km. Note, that EET-values imply the thickness of an elastic layer representing the rheology of the lithosphere, not the position of any strong layer. Modified after Sachsenhofer et al. (1996b). a. Isostatic model, b. EET= 0.25 km, c. EET= 2 km, d. EET= 5 km, e. EET= 15 km, f. Cross-sections "III" through the northern Fürstenfeld Basin and the Eisenberg Window (see Fig. 1 for location).

Sarmatian

During the Sarmatian the Styrian Basin remained marine, although with reduced salinity. Along the northern basin margin, marine environments interfingered with fluvial and lagoonal depositional settings. Marine conditions continued until the late Sarmatian (Fig. 2d) and were only interrupted when 30 m thick fluvial gravels were transported from a southwestern hinterland into the central Eastern Styrian Basin (Kollmann 1965, Skala 1967).

A Sarmatian phase of accelerated subsidence can be observed in large parts of the Eastern Styrian Basin and is missing only in the northern Fürstenfeld Basin and the Mureck Basin. It is interpreted as a second, but minor extensional phase (stretching factors <1.04; Fig. 4c). Evidence for late Sarmatian E-W directed extensional tectonics is found at the northern margin of the Gnas Basin (Krainer, 1984, 1987). According to the applied isostatic model the largest Sarmatian stretching factors occur at the basin flanks, whereas stretching factors in areas with high Ottnangian/Karpatian extension are small. This discrepancy disappears when lithospheric strength is taken into account and is an indication, that an entirely isostatic approach is not appropriate for the (post-Karpatian) evolution of the Styrian Basin. The increased lithospheric strength may be related to decreasing heat flow, which is 55 to 85 mW/m² since Sarmatian times (Figs. 5, 6a,b). However, the heat flow is still relatively high, probably due to thinned crust beneath the Styrian Basin.

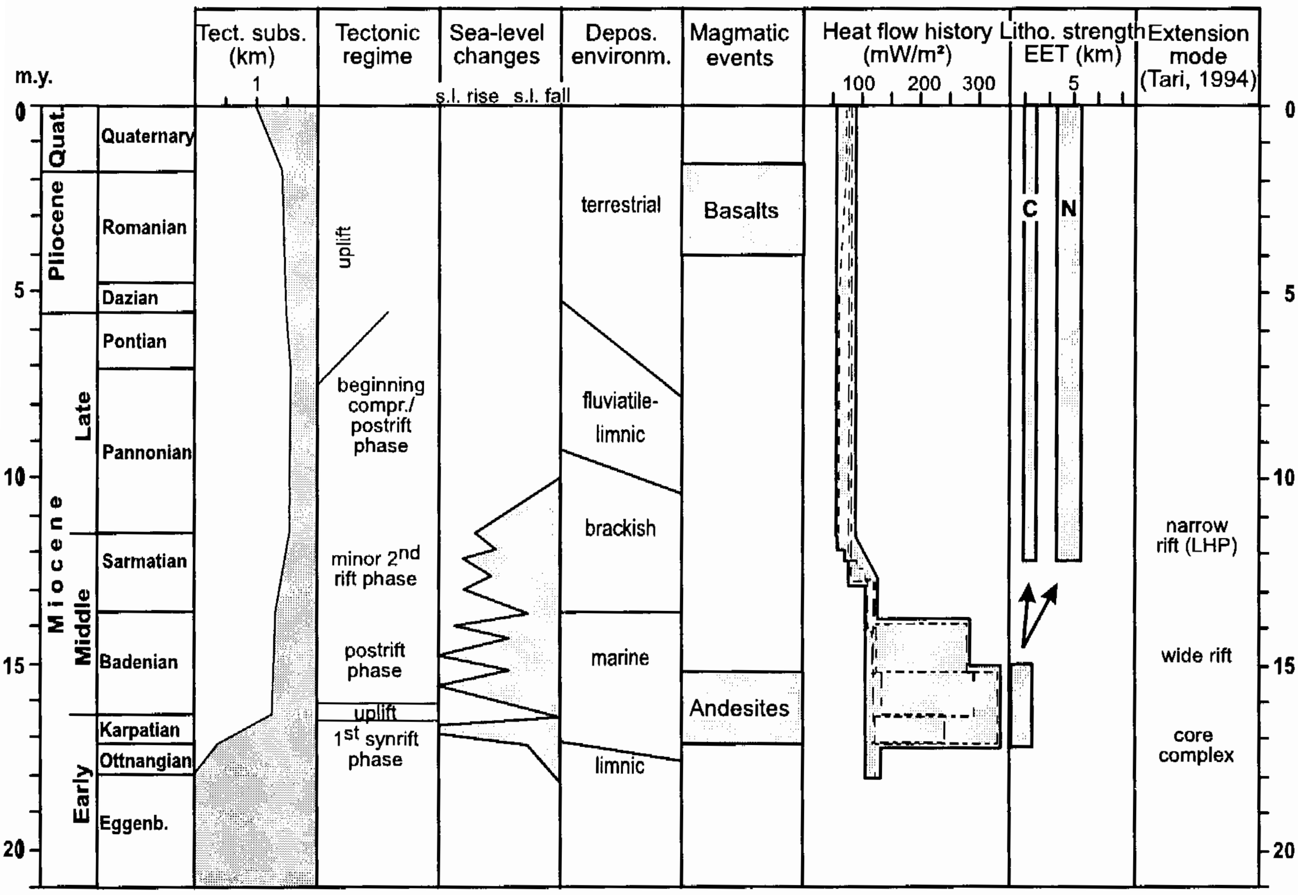

Fig. 8. Summary of the Neogene evolution of the Styrian Basin and the postulated extensional mode in the "Rába river extensional corridor" (Tari, 1994). EET: effective elastic thickness. N: Northern Fürstenfeld Basin; C: Central and Southern Fürstenfeld Basin.

Pannonian/Pontian

Tectonic subsidence in the Styrian Basin ended during the Pannonian (Fig. 3). (Thin) Pannonian sediments are restricted to the Eastern Styrian Basin (Fig. 2e). Salinity continued to decrease and marine conditions ended during the early Pannonian. Afterwards alluvial fans developed along the northern margin of the Eastern Styrian Basin and continued towards the south into an alluvial plain. Limnic and fluvial coal-bearing sediments of Middle Pannonian to Pontian age are restricted to the vicinity of the South Burgenland Swell (Fig. 2f).

In contradiction to the observed subsidence rates, the subsidence model (calibrated to Ottnangian to Sarmatian subsidence patterns) predicts a significant Pannonian to Quaternary subsidence (Fig. 3). This discrepancy reflects a major change in the stress field, related to a post-early Pannonian (7 m.y.) E-W compressional event in the Pannonian realm (Decker and Peresson, 1996; Peresson and Decker, 1996; this vol.). The peripheral parts of the Eastern Styrian Basin were downbended during Pannonian times (see cross-sections II and III; Figs. 5, 7f). This flexure is related to a Pannonian extension phase in the Little Hungarian Plain (Sachsenhofer et al., 1996b). The wavelength and the magnitude of the flexure indicate a Pannonian lithospheric strength in the northern Fürstenfeld Basin corresponding to about 5 km EET (Fig. 7d). This value fits well with estimates in other parts of the Pannonian realm (e.g. Lankreijer et al., 1996; van Balen and Cloetingh, 1994) and still points to a very weak lithosphere in comparison to many other sedimentary basins (cf. Cloetingh et al., 1995). Lithospheric strength in the central Fürstenfeld Basin (cross-section I; Fig. 5) was probably even lower. This difference may be an effect of higher heat flows in the central Fürstenfeld Basin (about 80 mW/m^2; Fig. 5), as compared to the northern Fürstenfeld Basin (65 mW/m^2; Sachsenhofer, 1994; see Fig. 6a,b).

Pliocene/Pleistocene

During the Pliocene the whole Styrian Basin was uplifted and erosion of a few hundred meter thick sediments started. At that time a second phase of volcanic activity produced nephelinitic/basanitic lava flows and a wide variety of pyroclastic rocks in the southeastern Styrian Basin (Fig. 2f). K/Ar-ages range from 1.7 ± 0.7 to 3.8 ± 0.4 m.y. (Balogh et al. 1994). According to Embey-Isztin and Dobosi (1995) the alkali basaltic magmas are dominated by liquids from the asthenosphere. Data from xenoliths suggest that their source was at a depth of 50 to 80 km within the subcrustal lithosphere (Kurat et al. 1980). Because of the great depth of the magma chamber, this volcanic event had no significant influence on the heat flow pattern. A slight heat flow increase (5 - 10 mW/m^2) during Pliocene or Pleistocene times (e.g. along cross-section II; Fig. 5) is probably a consequence of hydrodynamic effects (Goldbrunner, 1988).

Major uplift in the Styrian Basin started in the Quaternary. Intra-plate stress (Horvath et al, 1994) possibly in combination with detachment of the subducted slab (Tari et al., 1992) have been discussed as possible mechanisms for this young uplift along the margin of the Pannonian realm. Sediments of this time period are red palaeosoils, pre- and post-basaltic gravel (Winkler-Hermaden 1951) and synbasaltic crater lake fillings (Bertoldi et al. 1983, Pöschl 1991).

Summary

Fig. 9 summarizes different aspects of the Neogene evolution of the Styrian Basin and should stand for a summary chapter. Without repeating the above-mentioned ideas, the author would only like to emphasize, that the Styrian Basin provides good examples for the interaction between tectonic and thermal histories, i.e. the tectonic history strongly influences the heat flow history, but the heat flow history itself also strongly influences the tectonism.

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