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Geodynamic Controls on Deposition and Maturation of Coal in the Eastern Alps

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6 Figures

Abstract

Geodynamic processes control basin evolution and, therewith, coal-geological relevant parameters like number and geometry of seams and coal quality in terms of ash yield, sulphur content and maturity.

Only minor amounts of coal accumulated within the Eastern Alps during the Variscan orogeny in Carboniferous time and at the southern passive continental margin of Europe during Triassic and Liassic time. Jet formed after the Cretaceous orogeny in strike-slip controlled settings.

Major coal deposits in the Eastern Alps are related to basins, which formed during and after Tertiary continent-continent collision. A high number of thin seams was deposited in brackish environments in the Alpine foreland basin (Upper Bavarian coal district). The distribution of the seams is controlled by regressive/transgressive cycles. Non-marine coal in the Hausruck district formed during a late stage of the basin evolution.

Several intramontaneous pull-apart basins originated after the main collisional event. They often contain a single thick coal seam. In these basins, coal facies variations are primarily controlled by high subsidence rates, whereas coal facies variations in the Köflach area (Styrian basin) are controlled by local processes, like the lateral migration of channels.

The rank of pre-Tertiary coals ranges from sub-bituminous to semi-graphite and is a result of Mesozoic tectonothermal events. The rank of Tertiary coals is mainly controlled by Oligocene and Miocene heat flow. Extremely high heat flow was related to magmatic activity and the uplift of metamorphic core complexes. Tertiary coals in the vicinity to heat flow anomalies reach the bituminous stage in spite of shallow burial. In contrast, coal in the foreland basin, characterized by low heat flow, remained at low rank despite its deep burial.

Introduction

Both accumulation and maturation of coal are intimately related to the geodynamic evolution of the lithosphere. The accumulation of thick peat deposits requires specific tectonic conditions (e.g. subsidence rates, which are similar to peat accumulation rates; MCCABE, 1991; DIESSEL, 1992), and coalification, which is mainly controlled by the factors of temperature and time, is a consequence of heat flow and the depth of burial (e.g. TAYLOR et al., 1998).

The aim of this paper is to emphasize the relation between geodynamics and coal formation using the example of the Eastern Alps. Monographs of coal in the study area are provided by WEBER & WEISS (1983), SACHSENHOFER (1987) and SCHULZ & FUCHS (1991). Therefore, the present paper focuses on typical and/or economically important deposits. A simplified map of the Eastern Alps showing the distribution of main coal districts is presented in Fig. 1. Their stratigraphic age and the time of coalification are indicated in Fig. 2, together with some information on the geodynamic evolution of the study area.

Favourable conditions for the formation of coal occurred during different stages of the evolution of the Eastern Alps. This relation is dicussed in the first part of the paper. In the second part, the relation between geodynamics, heat flow and coal rank is highlighted.

Coal-producing environments and the geodynamic evolution of the Eastern Alps

Variscan evolution

The first peat forming stages during the evolution of the Eastern Alps are related to the final episodes of the Variscan orogeny (KRAINER, 1993; Fig. 2). Westphalian A-C coals accumulated in synorogenic settings ("foredeep") at the top of shallow marine sequences. Up to 9 seams interfinger with distributary bay and channel-fill deposits (RATSCHBACHER, 1987). Cretaceous low-grade metamorphism changed the organic matter to semi-graphite, which has been mined west of Leoben (Fig. 1). E-W directed intramontaneous basins formed after the Variscan orogeny and were filled with fluvial (Westphalian D to) Stephanian sediments. Thin coal seams in the Turrach and Steinach areas (east and west of the Tauern window) accumulated in flood plains and oxbow lakes on top of fining upward sequences (KRAINER, 1993). Minor Stephanian coal also occurs south of

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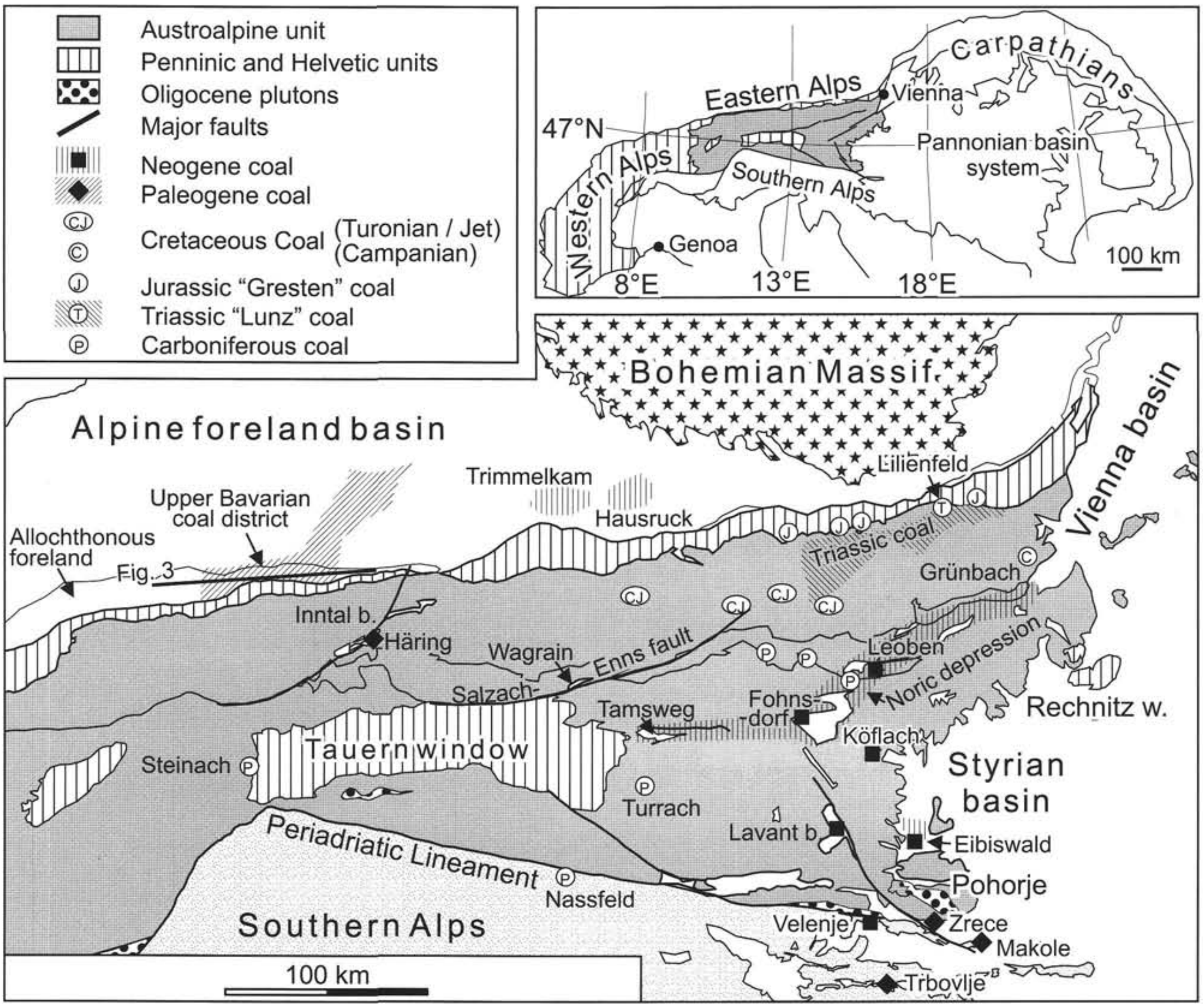


Fig. 1
Sketch map of the Eastern Alps and position of selected coal basins.

the Periadriatic Lineament in the Nassfeld area (Carnic Alps).

Alpine evolution

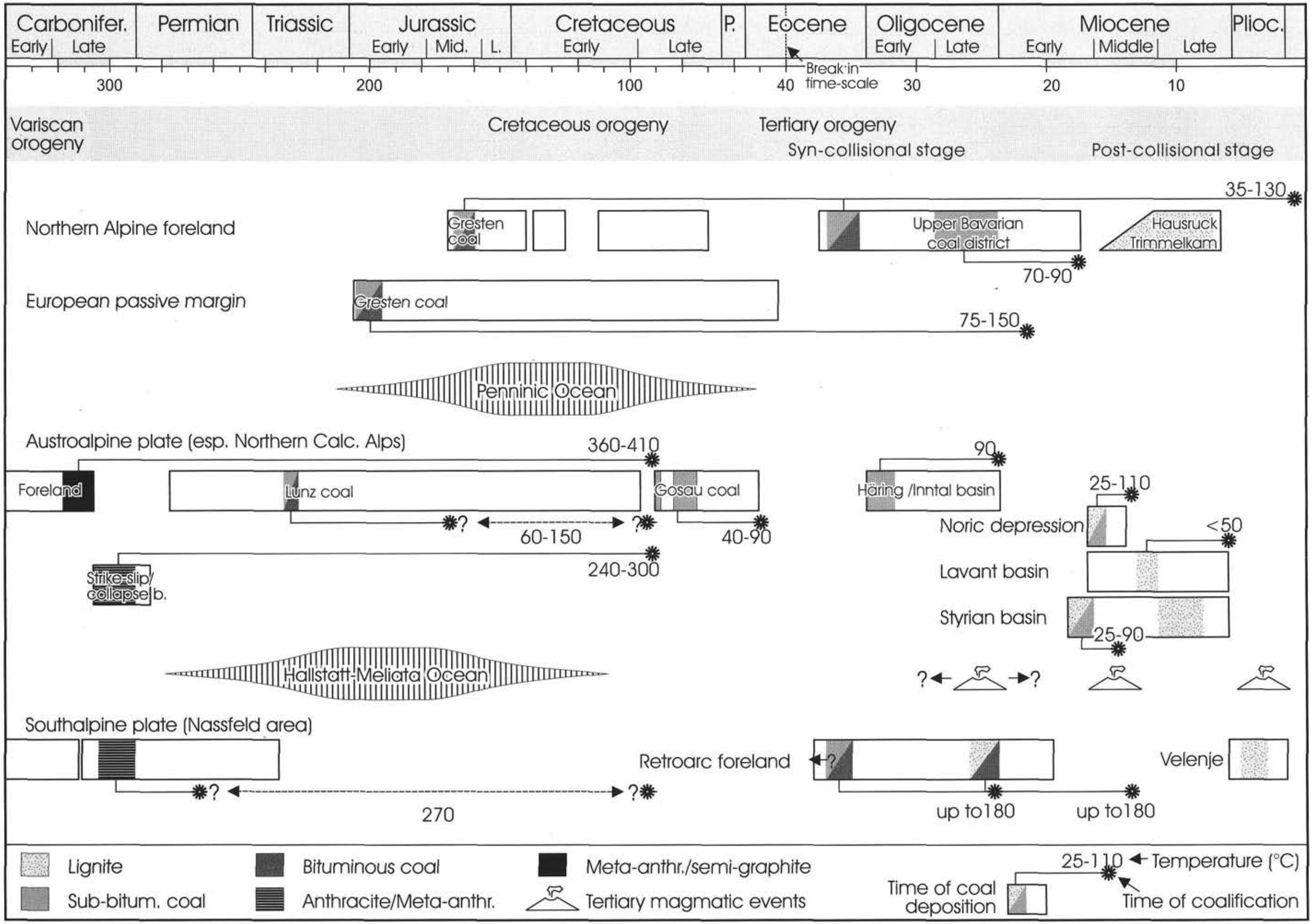
Rifting/drifting

The post-Variscan evolution started with Permian rifting and the opening of two oceans separating the Eastern and the Southern Alps during the Middle Triassic (Hallstatt/Meliata ocean) and the Eastern Alps and stable Europe during Early/Middle Jurassic times (Penninic ocean). Only minor coal deposits formed during this time interval (Fig. 2).

During the Late Triassic time the Northern Calcareous Alps formed the northern passive continental margin of the Hallstatt/Meliata ocean. Thick, mainly shallow-water, carbonates were deposited. A major sea level fall and tectonic events in Carnian time resulted in southward propagation of clastic sediments over the Austroalpine shelf region and the deposition of brackish "Lunz" coals (SACHSENHOFER, 1987). Today, these coals occur in different nappes within the northeastern Calcareous Alps (Fig. 1). The original thickness of the coal was in the order of a few tenths of centimeters. However, due to the Alpine orogeny, the coal forms up to 9 m thick lenses arranged along the crests of E-W trending anticlines in the Lilienfeld area.

Jurassic "Gresten" coals are related to a major phase of transgression caused by the opening of the Penninic ocean. Liassic sediments were deposited near the southern margin of stable Europe. They host coal seams, which formed either subaquatically, resulting in sapropelitic coal interfingering with marine limestones, or in relatively dry swamps within floodplain environments (SACHSENHOFER, 1987). Up to 16 seams with a maximum thickness of 1 m occur within the later facies realm. Tertiary tectonics transported the coal-bearing sequence to its present-day position near the northern margin of the Alps (Fig. 1). Gresten coals with a

Fig. 2 →
Overview showing the time of coal deposition, time of coalification, and coalification temperatures within the Eastern Alpine realm. The plot is mainly based on data published by SACHSENHOFER & RANTITSCH (1997). Note, that only magmatic events with a Tertiary age are indicated.


Carbonifer.
Early | Late
Permian
Triassic
Jurassic
Early | Mid. | L.
Cretaceous
Early | Late
P.
Eocene
Oligocene
Early | Late
Miocene
Early | Middle | Late
Plioc.
300
200
100
40
Break in time-scale
30
20
10
Variscan orogeny
Cretaceous orogeny
Tertiary orogeny
Syn-collisional stage
Post-collisional stage
Northern Alpine foreland
Gresten coal
Upper Bavarian coal district
Hausruck Trimmelkam
35-130
70-90
European passive margin
Gresten coal
75-150
Penninic Ocean
Austroalpine plate (esp. Northern Calc. Alps)
360-410
Foreland
Lunz coal
Gosau coal
60-150
40-90
90
Häring /Inntal basin
25-110
Noric depression
<50
Lavant basin
Styrian basin
25-90
Strike-slip/ collapse b.
240-300
Hallstatt-Meliata Ocean
Southalpine plate (Nassfeld area)
270
Retroarc foreland
up to180
up to180
Velenje
Lignite
Sub-bitum. coal
Bituminous coal
Anthracite/Meta-anthr.
Meta-anthr./semi-graphite
Tertiary magmatic events
25-110 ← Temperature (°C)
Time of coal deposition
Time of coalification

Doggerian age occur also in the autochthonous foreland beneath Tertiary sediments.

Cretaceous orogeny

Subduction of the Hallstatt/Meliata ocean and the Late Jurassic to Middle Cretaceous collision between the South and East Alpine blocks resulted in Cretaceous nappe stacking within the Austroalpine realm. Thereafter, subduction of the Penninic ocean beneath the active margin of the Austroalpine microplate began. Oblique subduction controlled the formation of Late Cretaceous Gosau basins on top of the Calcareous Alps (FAUPL & WAGREICH, 1996). No coal formed during the collisional event, but some deposits occur within the Gosau basins.

The coal-bearing Lower Gosau Group (Turonian to Campanian) comprises terrestrial to shallow marine deposits, which were laid down during a phase of major strike-slip faulting. Drift wood transformed into jet forms distinct layers within shallow marine Turonian sediments (KOLLMANN & SACHSENHOFER, 1998). Locally these layers, which were mined extensively during the 15th and 16th century (FREH, 1956), occur close to "usual" coal. Up to 8 coal seams also occur within deltaic sediments of Campanian age in the Grünbach area (SACHSENHOFER, 1987).

Tertiary orogeny: Syn-collisional stage

Following Late Cretaceous to Eocene subduction of the Penninic ocean, the Austroalpine block collided with stable Europe. The collision resulted in slab breakoff and magmatic activity along the Periadriatic Lineament (VON BLANKENBURG & DAVIES, 1995), nappe stacking, and the formation of the Northern Alpine foreland basin (Molasse basin). Coal deposition occurred during different stages of the evolution of the foreland basin:

- An up to 3 m thick Eocene coal seam formed during an early transgressive stage of its evolution and overlies a subsiding floodplain.
- Ongoing Oligocene collision resulted in increased subsidence of the foreland and a high relief in the Western Alps. Alpine detritus was delivered by alluvial fans into the basin and was transported by an axial drainage system in an eastward direction into the more than 1000 m deep sea. Late Oligocene coal intercalating with bituminous limestones accumulated near the shoreline in brackish environments. Mining activity was restricted to the allochthonous foreland (Upper Bavarian coal district). The total number of coal seams varies laterally between 20 and 60, but average seam thickness is only 0.3-0.5 m. The spatial distribution of the seams is controlled by regressive/transgressive cycles (GEISSLER, 1975; STEININGER et al., 1988/89; Fig. 3). The high number of seams, the control by regressive/transgressive cycles and intense tectonic deformation are common features of coal in foredeep settings (e.g. DIESSEL, 1992).
- The foreland basin was filled during the Early Miocene time. Middle to Late Miocene freshwater lignite was deposited in the Trimmelkam/Hausruck area during a late stage of basin evolution. The coal-bearing sequence overlies marine sediments with an erosional unconformity. Thickness and distribution of three up to 4 m thick coal

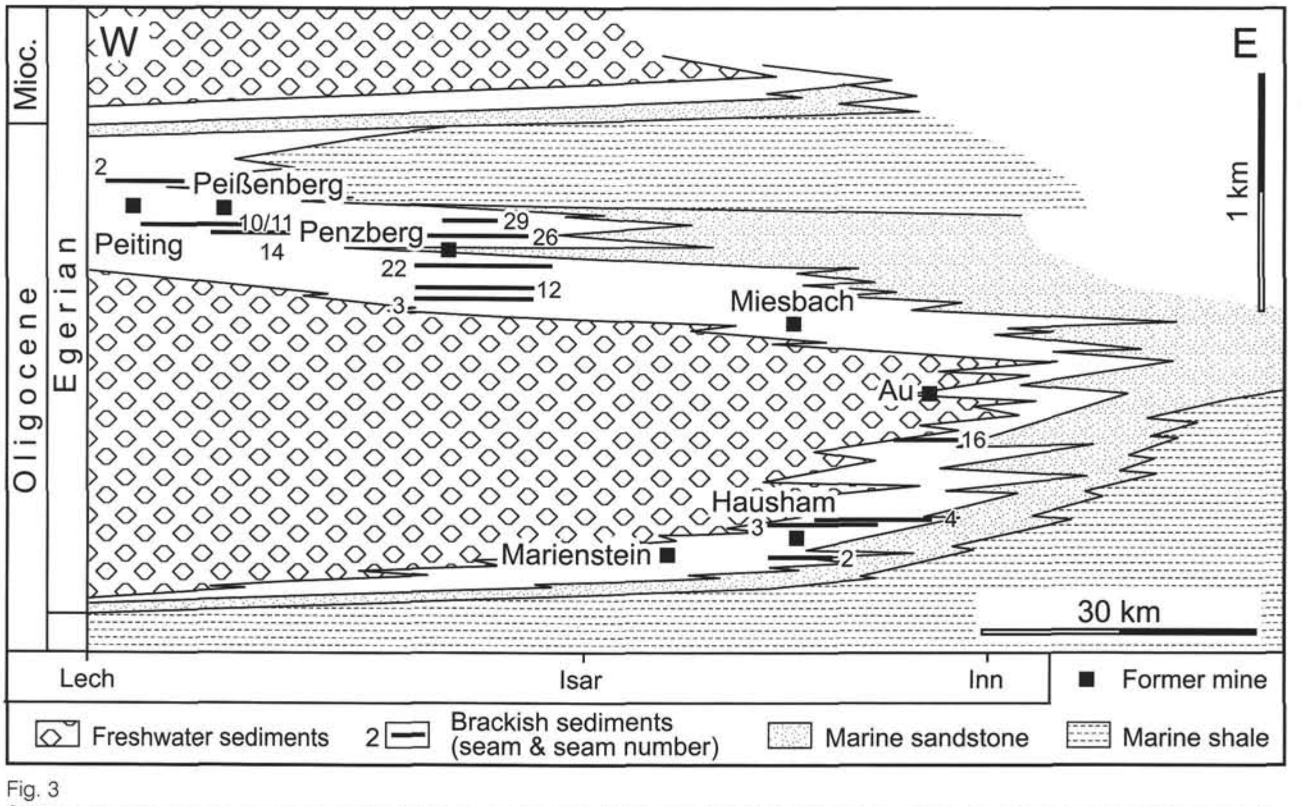


Fig. 3
Schematic W-E cross-section through the Upper Bavarian coal district (modified after GEISSLER, 1975). Position of cross-section is shown in Fig 1. Note, that positions of seams are shown only for the Hausham, Penzberg and Peiting areas. A high number of relatively thin seams is typical for foreland basins. The regional distribution of the deposits is controlled by regressions and transgressions.

seams are controlled by the underlying erosional relief (GROISS, 1989).

Oligocene coal also formed in the Inntal basin near Häring (Fig. 1), paleogeographically near the southern border of the foreland basin. Yet, because the basin is controlled by Early Oligocene transtension (ORTNER & SACHSENHOFER, 1996) rather than by flexure, it is discussed separately. Sedimentation started within an alluvial fan setting. The alluvial fan is overlain by a sulphur-rich seam, which shows a marine influence. Average thickness of the 1 km² wide seam is 4 m (max. 12 m). The coal grades upward into sapropelitic rocks and marls, which accumulated in a 200 m deep sea (STINGL & KROIS, 1991; Fig. 4).

Paleogene coals also formed north (Zrece) and south of the eastern section of the Periadriatic Lineament (e.g. Trbovlje, Makole in Slovenia; Fig. 1). According to TARI et al. (1993), the latter deposits formed in a retroarc-foreland basin.

Tertiary orogeny: Post-collisional stage

Final compression across the Eastern Alps in Miocene time was accomodated by orogen-parallel eastward extrusion of the central Eastern Alps along northeast (e.g. Salzach-Enns fault) and southeast trending strike-slip zones (e.g. Periadriatic Lineament; RATSCHBACHER et al., 1991). Intramontanous basins formed at oversteps of major strike-slip faults. Contemporaneously, E-W extension resulted in tectonic denudation and rapid uplift of metamorphic core complexes (Tauern and Rechnitz windows), formation of the Styrian basin and magmatic activity at the eastern margin of the Alps (TARI, 1994; EBNER & SACHSENHOFER,

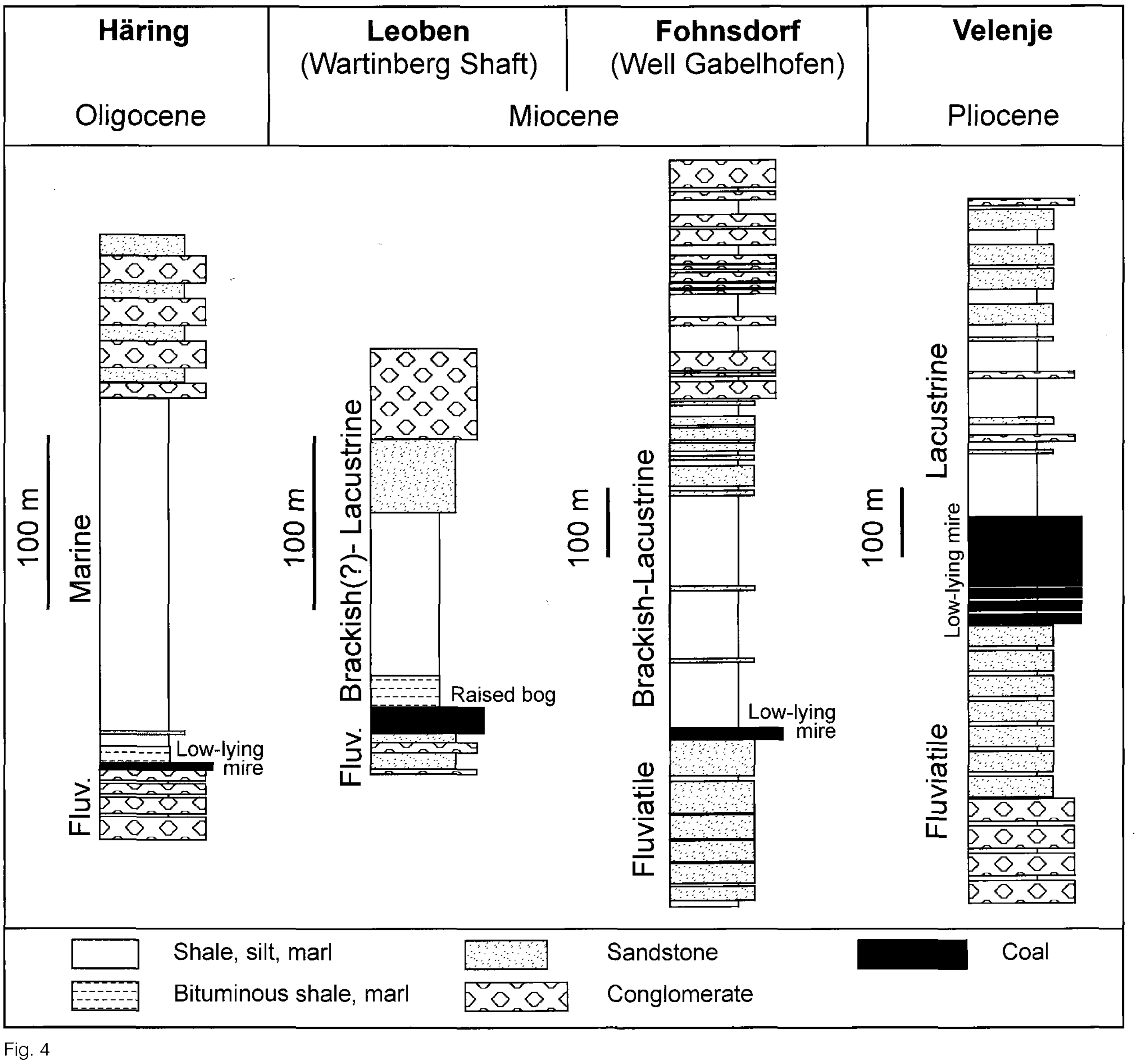


Fig. 4

Stratigraphic columns of coal-bearing pull-apart basins of Tertiary age and reconstruction of moor-types (STINGL & KROIS, 1991; SACHSENHOFER et al., a in press; LACKENSCHWEIGER, 1937; GRUBER & SACHSENHOFER, 1999; MARKIC & SACHSENHOFER, 1997).

In difference to foreland basins, only one, but thick seam is present. The sedimentary succession, controlled by high subsidence rates, indicates the drowning of the peat.

1995). Major coal deposits formed in strike-slip basins and in the Styrian basin.

Typically, Miocene basins along major strike-slip faults are filled from bottom to top by fluvial sediments, a single thick coal seam, a sapropelite, and lacustrine/brackish sediments (e.g. Leoben and Fohnsdorf basins in the Noric depression; Fig. 4). This sequence reflects the drowning of the peat due to high subsidence rates characteristic for pull-apart basins. Depending on the depositional environment, the coal properties differ significantly. Coal in the Leoben basin accumulated in a raised bog and is poor in ash and sulphur. Coal in the Fohnsdorf basin formed in a swamp influenced by a brackish lake and is rich in ash and sulphur.

Movements along the Periadriatic Lineament continued during the Pliocene (FODOR et al., 1999). They resulted in the formation of the deep Velenje pull-apart basin hosting a more than 100 m thick lignite seam (Fig. 4). Because of high subsidence rates and similarity to basins along the Noric depression it was filled with fluvial sediments, a drowning coal seam and lacustrine deposits (MARKIC & SACHSENHOFER, 1997).

Formation of the Lavant basin is related to Late Miocene movements along dextral strike-slip faults. From a coal-geological point of view, it differs significantly from other strike-slip basins. The main differences are a higher number (up to 5) of laterally more continuous, but relatively thin (generally 1-2 m), seams. Probably, the differences reflect differing subsidence rates.

Contemporaneously, with strike-slip faulting along the Noric depression, the Styrian basin formed on top of the eastward moving crustal wedge (EBNER & SACHSENHOFER, 1995). Several shallow (half)grabens formed in the Köflach area during the onset of basin formation and were filled with Early Miocene coal-bearing fluvial sediments (HAAS et al., 1998). The lateral continuity of the seams is low. They pinch out above basement highs, but reach a thickness up to 60 m within the depocenters. The diameter of the coal-bearing troughs ranges from 0.5 to 3 km. Coal facies variations are primarily due to local autosedimentational processes (e.g. migration of active channels), and not due to basin-wide events (KOLCON & SACHSENHOFER, 1999) indicating relatively low subsidence rates. More continuous seams formed at the same time in the Eibiswald area. Two lacustrine seams with a thickness ranging from 0.5 to 2 m have been mined. The upper seam, overlain by coastal plain deposits, reaches a lateral extension of ca. 25 km². Late Miocene lignite formed during final stages of the basin evolution in the central part of the Styrian basin. These fluvio-lacustrine coals reached only local significance.

Rank – a mirror of orogenic heat flow

Permian to Tertiary tectonothermal events are responsible for the different rank of coals in the Eastern Alps, which ranges from lignite to semi-graphite.

Pre-Oligocene tectonothermal events

Cretaceous temperatures in the Veitsch nappe were as high as 360-410 °C (RAITH & VALI, 1998) and resulted in the formation of semi-graphite. Due to significantly lower temperatures (<300 °C), coals in the Turrach and Steinach areas reach only the meta-anthracite stage (SACHSENHOFER & RANTITSCH, 1997). Similar Cretaceous temperatures occurred in the Nassfeld area, but RANTITSCH (1997) speculates that coalification occurred already during the Early Permian time as a result of strongly elevated heat flow.

The rank of Triassic "Lunz" coals in the northeastern part of the Northern Calcareous Alps ranges from sub-bituminous to medium volatile bituminous coal (0.43-1.20% vitrinite reflectance, Rr; Fig. 5). Coalification temperatures are in the range of 60-150 °C (Fig. 2). Isoreflectivity lines are

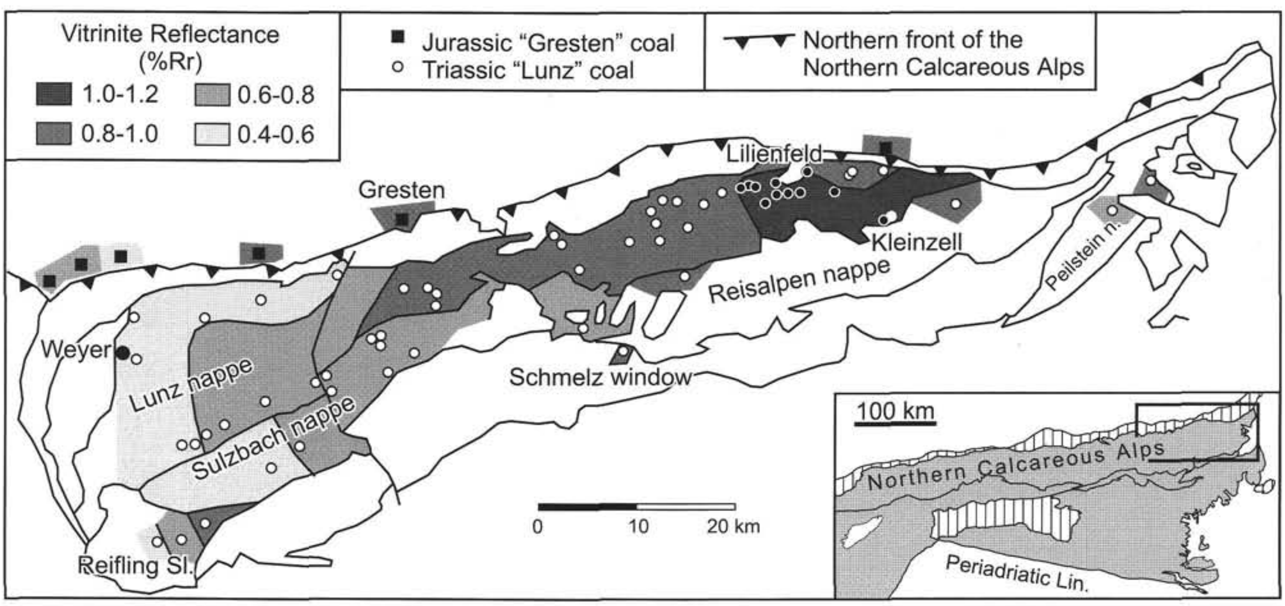


Fig. 5
Map showing vitrinite reflectance of Triassic "Lunz" coals in the northeastern part of the Northern Calcareous Alps and of Jurassic "Gresten" coals in the accretionary wedge north of the Northern Calcareous Alps (SACHSENHOFER, 1987).

displaced along nappe boundaries, indicating pre-tectonic coalification. An eastward increase in rank can be observed in all tectonic units. It is still unclear, whether this is a consequence of an eastward increase in tectonic burial during the Early Cretaceous time (closure of the Hallstatt/Meliata ocean) or a result of laterally varying Jurassic/Early Cretaceous heat flow.

Late Cretaceous "Gosau" coal reaches the sub-bituminous stage. Probably coalification ended before the Eocene deformation of the Gosau basins. Coalification temperatures were in the order of 40-90 °C, according to vitrinite reflectance studies.

Oligocene/Miocene heat flow

Coalification of Tertiary coals is controlled by Oligocene and Miocene heat flow patterns. During the last decade, heat flow histories of many basins were reconstructed applying numeric modelling techniques (YALCIN et al., 1997). SACHSENHOFER (in prep.) used this information together with vitrinite reflectance patterns of surface samples to design heat flow maps for Oligocene, Early/Middle Miocene and Late Miocene times (Fig. 6). Here, the maps are discussed with respect to the geodynamic evolution of the Alps and the resulting maturation patterns.

Oligocene

Oligocene heat flow patterns (Fig. 6A) exhibit a distinct asymmetry. Very low heat flow along the northern margin of the Eastern Alps, a thermal effect of nappe stacking and high sedimentation rates, contrasts with extremely elevated heat flow along their southern margin. The latter is a consequence of Oligocene magmatic activity.

The observed heat flow variations help to understand coalification patterns of Paleogene coals at the northern and southern edge of the Eastern Alps.

- Due to slightly elevated heat flow in the Inntal basin and extremely low heat flow in the allochthonous foreland basin, sub-bituminous coals (ca. 0.5%Rr) occur in Häring and in the Upper Bavarian coal district, although the latter was buried significantly deeper (>3 km; JACOB et al., 1982) than the Häring coal (<2 km; ORTNER & SACHSENHOFER, 1996).
- Maximum burial of the Eocene Zrece coal at the southern slope of the Pohorje Mountain was significantly below 1 km (HAMRLA, 1988). However, because of extremely elevated heat flow due to the emplacement of the Pohorje tonalite, the coal reaches the bituminous stage (0.8%Rr). Oligocene coal with an even higher rank (1.0%Rr) occurs close to an Oligocene volcanic center south of the Periadriatic Lineament. The rank of Oligocene coals decreases with the distance from the Periadriatic Lineament. Coal in the Trbovlje area is only a lignite (ca. 0.3%Rr).

Early/Middle Miocene

Tectonic turmoil during the Early/Middle Miocene time had a significant influence on heat flow patterns (Fig. 6B). Extremely elevated heat flow occurred in the vicinity of metamorphic core complexes (Tauern and Rechnitz windows). They result from rapid uplift of hot basement rocks (e.g. DUNKL et al., 1998). Extremely elevated heat flow (>200 mW/m^2) also occurred along the southeastern margin of the Alps. It is at least partly a result of magmatic activity (SACHSENHOFER, 1994). However, maximum heat flow occurs south of the center of magmatic activity. There are two alternative interpretations. Both, a shallow pluton that is unknown up to now, beneath the heat flow maximum and another metamorphic core complex could explain the observed anomaly (SACHSENHOFER et al., 1998). In contrast to the above areas, the northern margin of the Alps remained cold. Slightly elevated heat flow along the northern rim of the foreland basin is probably an effect of northward migration of temperated fluids from beneath the Alps.

Early/Middle Miocene heat flow controls coalification of Early Miocene coals in intramontaneous basins and in the Styrian basin:

- Bituminous coal (0.65%Rr) occurs in the western Enns valley (Wagrain) and in the western Noric depression (Tamsweg), whereas lignite occurs in more eastern basins. Westward increase in rank is a consequence of the heat flow maximum above the uplifting Tauern window. Whereas rank decreases continually with the distance from the Tauern window in the Enns valley, coalification patterns are more complicated along the Noric depression. This is due to a local heat flow high in the Leoben area and an exceptionally thick basin fill in the Fohnsdorf basin (SACHSENHOFER, 1992; SACHSENHOFER et al. a, in press). Both effects resulted in a similar rank (sub-bituminous coal, 0.40-0.55%Rr).
- Early Miocene Eibiswald coals in the southwestern Styrian basin are located at the margin of a huge heat flow anomaly. Therefore, these are sub-bituminous coals (0.4-0.55%Rr), whereas Early Miocene Köflach coals in the northeastern part of the basin are only lignites (0.30%Rr). Coal in the Makole area is located within the heat flow anomaly and even reached the medium volatile bituminous stage (1.4%Rr; SACHSENHOFER et al., b, in press).
- The rank of Oligocene coals along the southern and eastern margins of the Bohemian massif is locally raised (up to 0.55%Rr). Perhaps this is due to the described northward migration of temperated fluids and slightly elevated heat flow along the northern rim of the foreland basin.

The rank of Jurassic "Gresten" coals ranges from sub-bituminous (0.55%Rr) to high volatile bituminous coal (1.0%Rr; Fig. 4). These coals probably matured during deep (3-5 km?) early Miocene burial.

Late Miocene

Heat flow decreased during the Middle and Late Miocene time in the central and southeastern part of the Eastern Alps (Fig. 6C). In the Styrian Basin heat flow was elevated above basement highs (up to 100 mW/m^2), and 60 to 70 mW/m^2 in troughs with thick Neogene sediments. The relatively high heat flow is a result of thinned crust beneath the Pannonian basin.

Because of relatively low heat flows and shallow burial, all post-Early Miocene coal deposits contain lignite. The heat flow in the foreland basin has been low since Oligocene times. Consequently, the rank of deeply buried Eocene coal at the base of its Tertiary fill is low and a vitrinite reflectance of 0.6%Rr is reached only below thrust sheets at ca. 4 km depth.

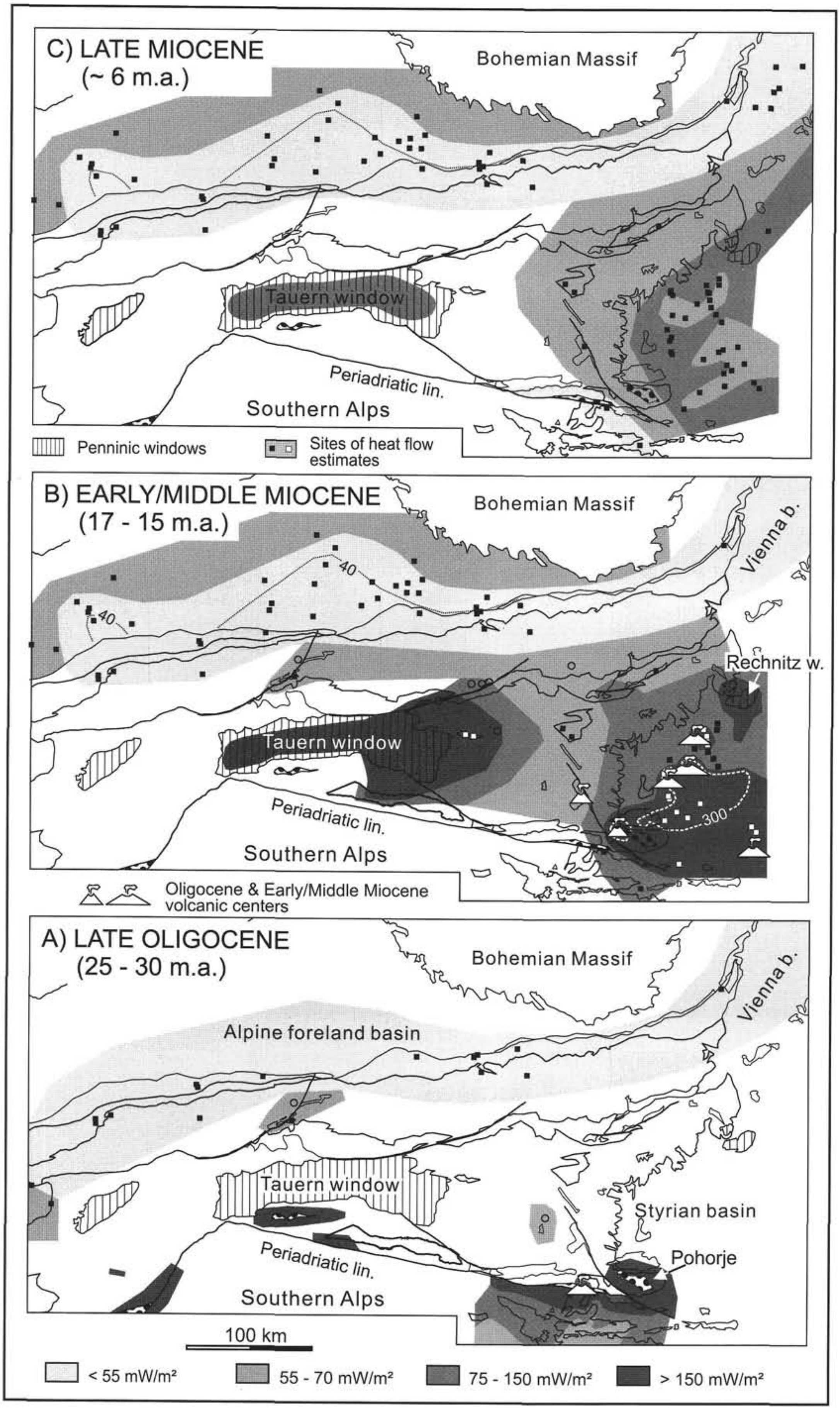


Fig. 6
Heat flow maps of the Eastern Alps and adjacent areas for A) Oligocene, B) Early/Middle Miocene, and C) Late Miocene times (SACHSENHOFER in prep.). The maps are based on data from DOLL et al. (1997), DUNKL et al. (1998), EDER et al. (1999), FERREIRO-MÄHLMANN (1994), FÜGENSCHUH (1995), FRANCU et al. (1990), HASENHÜTTL et al. (in press), HILTMANN et al. (1995), JACOB et al. (1982), LADWEIN et al. (1991), ORTNER & SACHSENHOFER (1996), SACHSENHOFER (1994), SACHSENHOFER & RANTITSCH (1997), SACHSENHOFER et al. (a, b in press), SCHMIDT & ERDOGAN (1993, 1996), WAGNER et al. (1986), and unpublished data.

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