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Palaeoenvironmental Studies in the Early Miocene Lignite Opencast Mine Oberdorf (N Voitsberg, Styria, Austria)

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Styria
Pannonian Basin
Styrian Basin
Lignite
Miocene
Palaeoenvironment
Palaeoclimate

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Studien zum Paläoenvironment im untermiozänen Braunkohlentagebau Oberdorf (N Voitsberg, Steiermark, Österreich)

Zusammenfassung

Die Subsidenz des Beckens von Köflach-Voitsberg wurde durch NE-gerichtete Extension und die Bildung von flachen Gräben und Halbgräben verursacht. Diese tektonischen Vorgänge fallen mit dem Beginn des seitlichen Ausweichens des Steirischen Krustenkeiles im Untermiozän zusammen. Im Bereich des Tagebaues Oberdorf entstanden durch Abschiebungen flache Senken, denen das lokale Entwässerungssystem folgte.

Die Untersuchung der Ablagerungsbedingungen der Braunkohle-führenden Köflach-Voitsberg-Formation belegt eine fluviatile Randfazies. Sedimente der Überflutungsebene und flacher Überflutungsdepressionen wechseln mit Dammdurchbruchsedimenten und Rinnensedimenten.

Paläoböden treten häufig auf und zeigen überwiegend Charakteristika von wassergesättigten Böden.

Das ca. 30 m mächtige Braunkohleflöz besteht überwiegend aus xylo-detritischer Kohle. Es entstand in einem relativ feuchten Niedermoor mit relativ hohem pH-Wert. Fast alle Bereiche der Braunkohle-führenden Sedimentabfolge beinhalten zahlreiche Pflanzenfossilien (Diasporen, Blätter und Palynomorpha). Die Arten-Spektren bestehen zum größten Teil aus Gehölzen. Krautige Elemente des Waldbodens oder einer Riedfazies und Wasserpflanzen sind nur durch Pollen und Sporen belegt. Im Diasporen-Spektrum sind diese Elemente selten und nur durch wenige Taxa vertreten. Unter den Blattresten fehlen sie mit Ausnahme einiger Farne. Die Rekonstruktion des Paläoklimas ergab eine durchschnittliche Jahrestemperatur von 14–17°C und durchschnittliche jährliche Niederschläge von 1000–2000 mm.

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Die beiden Wirbeltierfaunen aus der Ostmulde sind sehr reich an Amphibien, Echsen, Schlangen und Säugetieren. Über 80 Wirbeltierarten sind fast ausschließlich durch isolierte Zähne und Einzelknochen belegt. Diese Auswahl und die Art der Konzentration der Fossilien verstehen wir als Ergebnis taphonomischer Prozesse. Die meisten Säugetiere waren Pflanzenfresser, zum Teil auch Alles- und Insektenfresser. Sie nützten die Wälder als Lebensraum und ihr reiches Angebot an Früchten, Beeren, Samen, Blättern und Wurzeln als Nahrung. Die Mehrzahl der Kleinwirbeltiere dürfte unter der Erde in Grabgängen, im Gebüsch und unter vermodernden Bäumen gelebt haben, während die Flughörnchen hohe Bäume für ihre Aktivitäten benötigten.

Abstract

Subsidence of the Köflach-Voitsberg Basin was related to NE-directed extension and to the formation of shallow (half)grabens. In the Oberdorf area extension created shallow depressions which controlled the local drainage pattern. Extensional faulting occurred during the incipient lateral movement of the Styrian crustal wedge between the Mur-Mürz- and the Lavanttal faults.

The Early Miocene lignite-bearing Köflach-Voitsberg Formation originated in a marginal fluvial environment with floodplain- and floodbasin sediments alternating with crevasse splay deposits and channel fillings. Palaeosols with characteristics of temporarily waterlogged soils occur frequently.

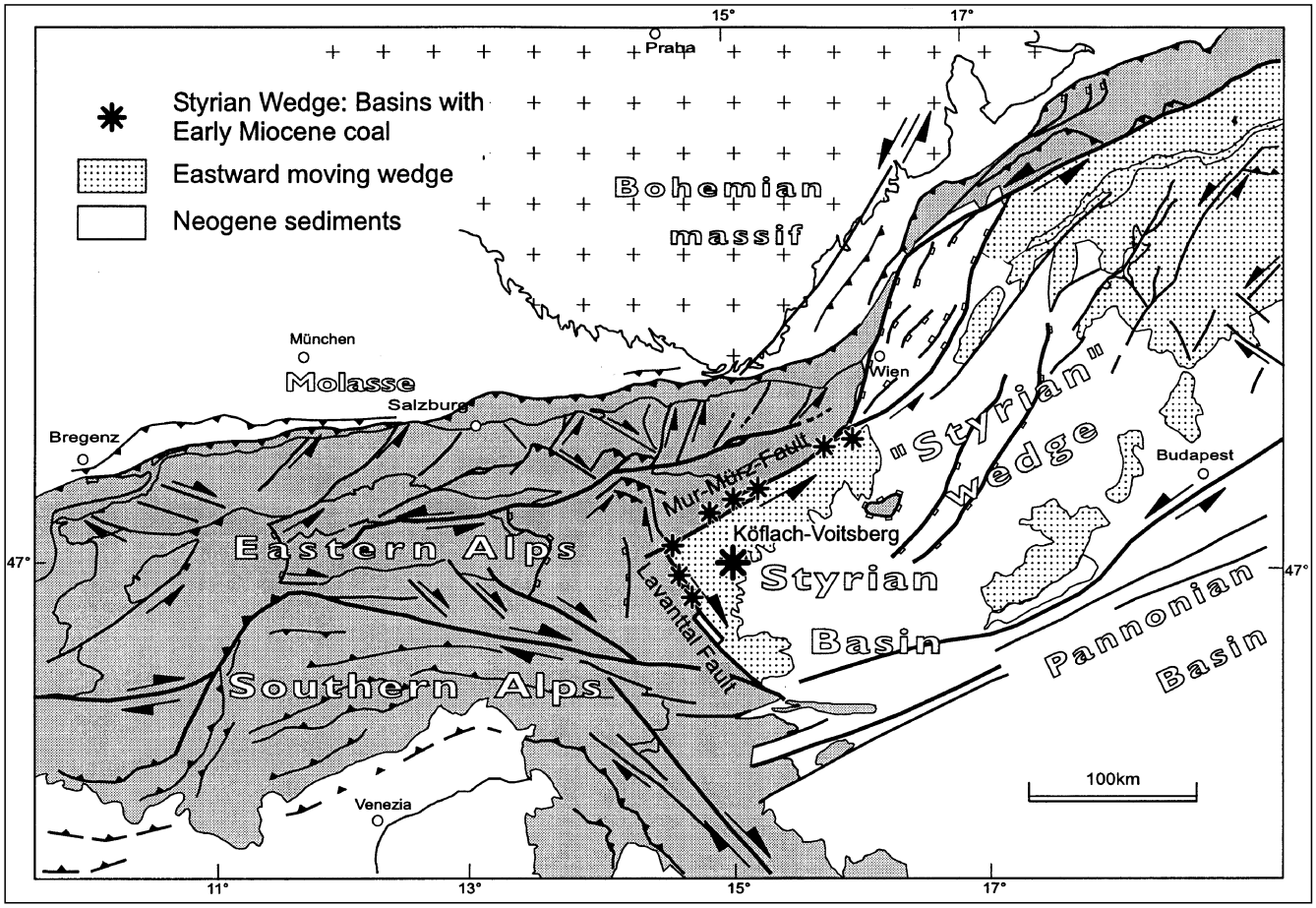
The circa 30 m thick lignite seam consists mainly of xylo-detritic coal. Coal-petrographic data show that it originated in a relatively wet low-moor with relatively high pH-values.

The lignite-bearing sequence in the Oberdorf opencast mine is extremely rich in fossil plant remains (diaspores, leaves and palynomorphs) at almost all levels. Woody genera are dominant. Herbaceous elements reflecting forest floor or reed-like facies and aquatic plants are well represented in the pollen record. In the diaspore record, they generally occur rarely and are species poor. With the exception of some ferns leaf remains of herbs are lacking . The palaeoclimatic conditions are estimated at 14–17°C mean annual temperature and 1000–2000 mm mean annual precipitation.

Two vertebrate faunas from the hanging wall of the eastern sub-basin are very rich in amphibians, lizards, snakes and mammals. More than 80 vertebrate species are recorded, almost exclusively from isolated teeth and inarticulated bones. This kind of selection and concentration of fossils is interpreted as a result of taphonomic processes. Although some were omnivorous or insectivorous, most of the mammals were plant eaters using the forest environments for living and their rich supply of fruits, berries, seeds, leaves and roots for food. The majority of the small vertebrates is thought to have lived in burrows underground or in bushes and under rotting logs, while the flying squirrels needed high trees for their activities.

1. Introduction

The investigated coal basin of the Köflach/Voitsberg area is situated in the northwesternmost part of the Styrian Basin, which forms part of the Pannonian Basin System (Text-Fig. 1). The latter is predominantly filled with paratethyian marine deposits (EBNER & STINGL, this vol.).



Text-Fig. 1.
Miocene tectonic map of the Eastern Alps, the adjacent Western Carpathians and the Pannonian Basin (redrawn after PERESSON & DECKER, 1997). Dashed areas show the Styrian crustal wedge which started to move eastwards between the Mur/Mürz/Vienna Basin transform and the Lavanttal fault system during the Ottnangian–Karpatian. On this wedge, coal-bearing basins evolved along the bounding strike-slip faults and in the Styrian Basin.

However, the lignite-bearing sediments of the Early Miocene Köflach-Voitsberg Formation are fluvial-limnic deposits and lie in the Oberdorf Basin which is divided into a western and an eastern sub-basin. These sediments reach a thickness of more than 300 m in the Oberdorf opencast mine (Text-Fig. 3).

The reconstruction of the palaeoenvironment is based on palaeobotanical (KOVAR-EDER, this vol., MELLER, this vol., ZETTER, this vol.), palaeozoological (DAXNER-HÖCK, this vol.), coal-petrographical (KOLCON & SACHSENHOFER, this vol.). and sedimentological data (HAAS, this vol.). The data were obtained from material of the eastern sub-basin, using borehole and outcrop samples from the footwall sediments, the coal seam, the main parting, and the hanging wall sediments (additional palaeobotanical data derive from the western sub-basin). Palaeozoological investigations were restricted to the hanging wall sediments, where the only layers rich in remains of small mammals were found.

The rich vertebrate assemblages in the middle part of the hanging wall sediments are indicative of Neogene Mammal Zone MN4 (DAXNER-HÖCK, 1998). Palaeomagnetic investigations show that the footwall sequence and the lower part of the hanging wall sediments are reversely magnetized, while the upper part of the hanging wall is normally magnetized (MAURITSCH & SCHOLGER, this vol.). The latter is correlated by the vertebrate assemblages with Chron C5Dn and the lower, reversely magnetized part, with Chron C5Dr. According to the GPTS (Geomagnetic Polarity Time Scale), the polarity change C5Dr/C5Dn is 17.6 m.a. old. This is indicative of an Ottnangian age according to the Central Paratethys Time Scale (STEININGER et al., this vol.). Furthermore the palaeomagnetic investigations provide evidence for an Ottnangian position of the Oberdorf Basin at 34° + 5° northern latitude and a counterclockwise rotation of 20° (MAURITSCH & SCHOLGER, this vol.).

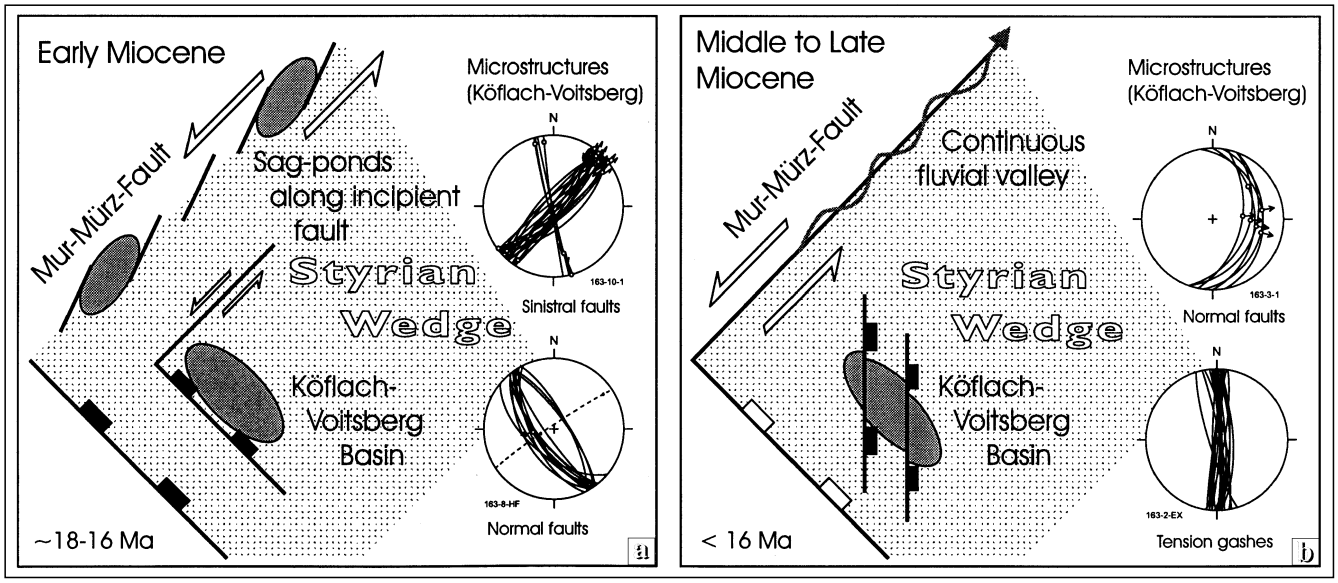
2. Early Miocene Tectonics and Basin Formation

During the Early Miocene, a number of sedimentary basins started to subside almost synchronously on top of the thrust wedge of the easternmost Alps. These basins include the Styrian Basin, the Vienna Basin, and the basins along the Mur-Mürz- and Lavanttal fault systems (Text-Fig. 1).

The basal sequences of several basins along the Mur-Mürz fault ("Noric depression"), the Lavanttal fault, and the Styrian basin (Köflach-Voitsberg) contain freshwater coal seams. Both, basin formation and the formation of sedimentary environments favourable for coal accumulation, are related to the regional Miocene tectonic evolution at the Alpine/Pannonian transition.

Early Miocene tectonics of the Eastern Alps were characterized by the cessation of the imbrication of the Molasse Basin and by the onset of (N)E-directed lateral movement of the "Styrian" crustal wedge (Text-Fig. 1; DECKER & PERESSON, 1997).

This wedge moved along the sinistral NE-striking Mur-Mürz-Vienna Basin transform system, and the dextral SE-striking Lavanttal-fault (Text-Fig. 1). Northeast- and eastward motion was associated with NE- and E-directed extension and with detachment faulting. This resulted in the formation of the Styrian Basin. Along the Mur-Mürz wrench fault system, several isolated small basins formed during the Early Miocene. Basin subsidence occurred along the new-forming wrench fault which cut through a hilly lowland (compare FRISCH et al., in press). Incipient basin subsidence presumedly was related to the formation of isolated sag ponds between overstepping and propagating fault segments (Text-Fig. 2). Such ponds are known to host wetlands and peats which can evolve into lakes catching the local drainage system.



Text-Fig. 2a.
Tectonics of the Styrian wedge during Early Miocene.
The formation of coal-bearing basins along the Mur/Mürz fault is related to the formation of sag ponds along the incipient fault zone. The normal faults and strike-slip faults which were measured in the Köflach and Zangtal pits indicate prominent sinistral faulting along NE-striking faults and NE–SW-directed extension by normal faulting. These structures may be related to the formation of the Early Miocene Styrian Basin. Plots are lower hemisphere Schmid projections with great circles indicating fault planes, points and arrows indicate slickensides and the slip direction, respectively.

Text-Fig. 2b.
Tectonics of the Styrian wedge from Middle to Late Miocene.
The isolated basins along the Mur/Mürz fault have linked up to a continuous fluvial valley. Normal faults and tension gashes measured in the Köflach and Zangtal pits indicate a change of extension directions to E-directed extension.

The coal-bearing sequences of the Köflach-Voitsberg Basin overlie crystalline and Palaeozoic basement units. Sedimentation started with a low-gradient fluvial sequence indicative of a lowland palaeoenvironment with moderate relief energy. The coal-bearing basin was situated in the interior of the extruding Styrian wedge, apart from the main boundary faults of the Mur-Mürz valley. The sediments formed in a generally NW–SE-trending embayment at the western border of the Styrian Basin which may reflect the original basin shape. The main deformation structures seen in the Köflach-Voitsberg opencast mine are NE-striking sinistral wrench faults, NW-striking normal faults paralleling the general basin strike (NE-directed extension), and younger E-dipping normal faults. Older, NE-directed extension is related to Miocene crustal thinning and detachment faulting during incipient movement of the Styrian wedge. For the Early Miocene NE–SW-extensional event, low extension values are estimated from the observed structures. Normal faults and tension gashes within the coal seams indicate less than 10 % horizontal extension. These values are corroborated by the absence of high-energy sediments which would indicate pronounced fault scarps. We therefore propose that NE–SW-directed extension and normal faulting led to the formation of shallow depressions as grabens or half grabens within a hilly lowland which were filled up with coal-bearing fluvial and limnic sequences (Text-Fig. 2a). Younger, E-directed extensional structures truncating the older structures (Text-Fig. 2b) cannot be related to the formation of the coal basin. These structures have been dated as Middle to Late Miocene (compare DECKER, 1996).

3. Palaeoenvironmental Reconstruction of the Eastern Sub-Basin

3.1. Footwall

The footwall sediments in the eastern sub-basin of the Oberdorf opencast mine have been assigned to a marginal facies of a fluvial environment (Text-Fig. 3, and HAAS, this vol., Text-Fig. 3).

The change from basal channel deposits to overbank sediments (crevasse – floodplain sediments) in the upper units reflects the decrease of the immediate fluvial influence. The general fining upward within the sequence is initiated by a short-term coarsening upward deposit, reflecting the start of a fluvial influence. Siderite occurs as radially organized, spherical structures with a series of concentric shells. The occurrence of siderite ooids can be explained as secondary precipitation in waterlogged soils in a back swamp (HAAS, this vol., DAXNER-HÖCK et al. 1998).

The mineralogy of a sediment with a lapilli-like structure in an approximately 3 to 7 cm thick layer in the uppermost part of the footwall sediments showed an already completely altered material with a 97 % kaolinite content. Further investigations, such as REE (rare earth element) analyses are in progress to determine from which volcanic province the lapilli tuff derived.

The cyclic appearance of horizons with diagenetically altered, oxidized organic material reflects the occurrence of former root horizons. The frequent occurrence of fusain (fossil charcoal) layers may indicate forest fires, which are known to occur regularly in recent subtropical to tropical swamps. Most of the investigated fusain particles showed early-wood deformation, but intact zones of late-wood with little influence of lignification occur as well. CICHOCKI (this vol.) argues that these particles probably did not derive from trees in living positions, but rather from variably degraded fallen wood. This suggestion is also supported by the very selective spectrum of wood species.

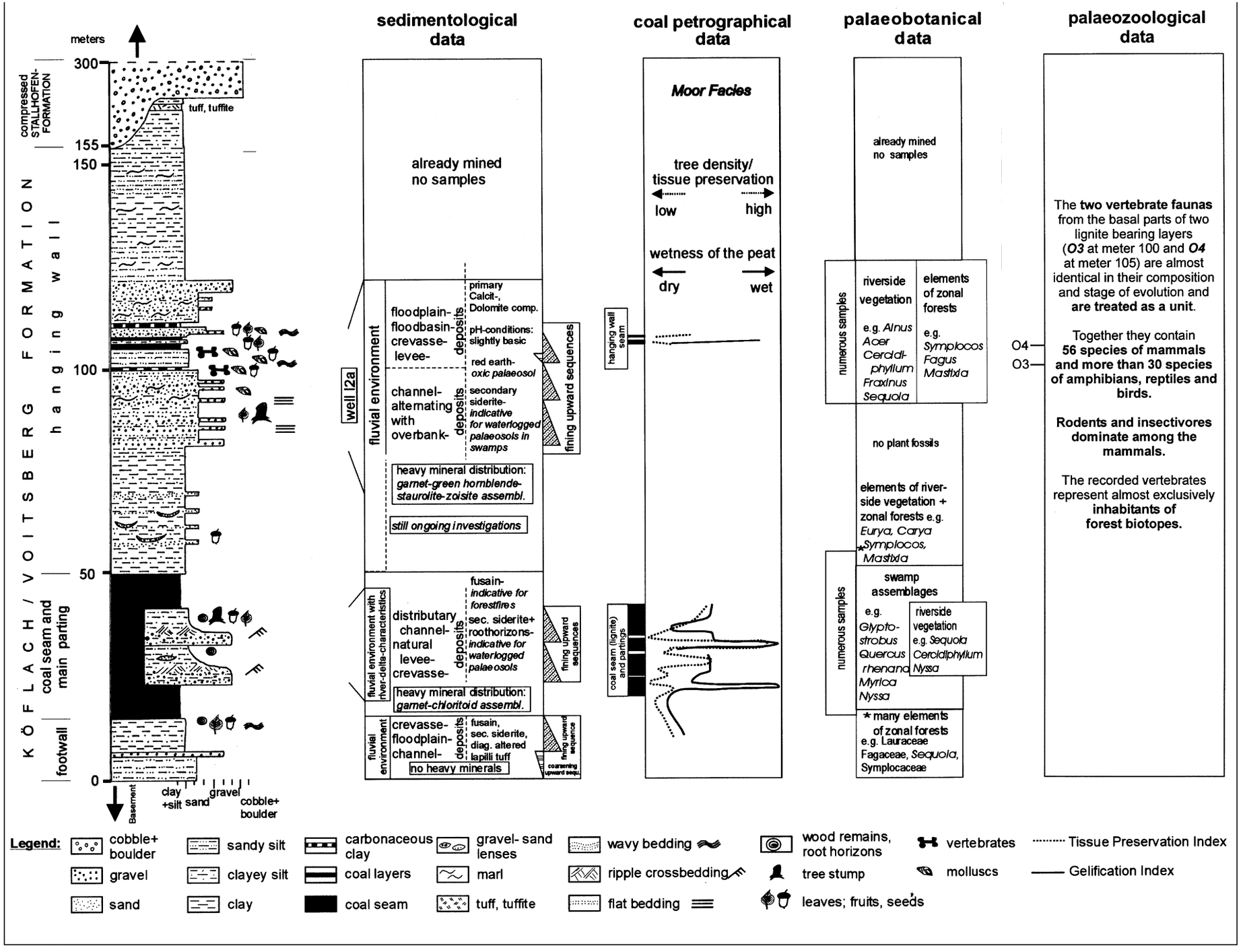
At the top of the footwall sediments and at the base of the coal seam, species-rich mesophytic forests represented mostly by evergreen trees and shrubs are best documented (e.g. Fagaceae, Lauraceae, Mastixiaceae, Rutaceae, Sapotaceae, Symplocaceae, Styracaceae). Some of these taxa have not been discovered in the subsequent following sedimentary sequence (Lauraceae, *Trigonobalanopsis* leaves, *Symplocos poppeana* KIRCHHEIMER, *Symplocos* cf. *pseudogregaria* KIRCHHEIMER). Azonal habitats are less well represented here e.g. *Glyptostrobus, Myrica, Nyssa, Ilex, Sequoia, Symplocos*. Submerged aquatic associations are exclusively documented by *Ceratophyllum, Potamogeton* and *Stratiotes*. Heavily fragmented leaves, indicative of significant mechanical stress (e.g. transport at higher energetic level), are characteristic of these layers. Several diaspore taxa are represented only by a few specimens. This fact could be caused by transport selection and/or by their original accessory occurrence in the vegetation. The sedimentological analysis of this part of the sequence indicates low-energy floodplain and crevasse deposits, where the probably fluviatile transported and fragmented leaves would have been finally deposited.

3.2. Coal Seam

Coal-petrographic data and the high ash-content of the lignite prove a topogenous setting of the former peat. The most abundant macrolithotype is xylo-detritic coal (detritic plant material with a considerable content in xylitic particles). Fusain (fossil charcoal) is present in thin layers. The accumulation of the lignite was often interrupted by flooding events, which produced numerous seam splittings. Carbonate-rich waters from the north (Graz Palaeozoic) increased the pH-value of the swamp. This, and a concentration of sulphate-rich waters at the impermeable base of the seams are responsible for relatively high sulphur-contents.

Facies indicators based on maceral analysis show frequent changes in gelification of the lignite (indicative for the wetness of the swamp) and in tissue preservation (indicative for tree density; Text-Fig. 3). However, an overall upward increase in tissue preservation can be observed in both, the lower and the upper coal seams. Most abundant are pollen from mixed mesophytic forests and from swamp forests. There is little variation in relative frequencies of plant communities with depth. However, the percentage of Taxodiaceae-Cupressaceae also shows a clear upward increase within the upper seam (KOLCON & SACHSENHOFER, this vol., Text-Fig. 3), emphasizing that the parallel increase in tissue preservation is mainly due to increasing tree (conifer) density. The ratio of presumably deciduous versus evergreen plants is close to 1. This is characteristic of warm-temperate sub-tropical and humid climates.

Palaeobotanical investigations give further information describing the lignitic, silty to clayey seam partings to be species poor, and usually dominated by *Glyptostrobus europaeus* (BRONGNIART) UNGER (diaspore record), reflecting woody swamp habitats. In the leaf assemblages, *Quercus rhenana* (KRÄUSEL et WEYLAND) KNOBLOCH et KVACEK is often monodominant, generally associated with *Glyptostrobus* and few accessory elements (*Myrica, Fraxinus*), document-



Text-Fig. 3.
Palaeoenvironmental reconstruction of the Early Miocene Köflach/Voitsberg formation in the open cast mine Oberdorf by sedimentological, coal petrographical, palaeobotanical and palaeozoological data.

ing a successional stage of the lignite-forming vegetation. The diaspore spectra are more variable, indicating swamp and riverside forests. The main elements are *Glyptostrobus, Sequoia, Myrica, Rubus, Nyssa*, and *Sparganium*. Occasionally represented are *Salix, Pterocarya* s.l., Viscaceae, *Prunus, Cercidiphyllum* and Araceae. Findings of other taxa are rarer here. The palynomorph records reflect also swamp forests and shrubby peat-swamps. However, about 50 % of the documented palynomorph taxa indicate mesophytic forests. These pollen may derive from more distant areas.

3.3. Main Parting

The sandy-silty development of the main parting (Text-Fig. 3, and HAAS, this vol., Text-Fig. 5) differs considerably from the silty-clayey development of the footwall sediments. The sedimentary facies points to a fluvial marginal environment with subordinate characteristics of a river-delta-environment. The sediments of the main parting are comparable to recent distributary channel deposits, natural levee- and crevasse deposits. The heavy mineral distribution defines a low-grade-metamorphic source area with a characteristic garnet-chloritoid assemblage. The erosion of calcalpine sediments (Kainach Gosau, upper Cretaceous–Eocene units) can also be taken into account for the definition of the source area. The increased organic sedimentation in the upper part is documented by elevated organic carbon contents (up to 3 %) in the siliciclastic sediments. This is due to both plant detritus, including drifted wood remains, and partly diagenetically altered root horizons. Secondary precipitated siderite, a palaeoenvironmental indicator for waterlogged soils, as well as fusain occur occasionally.

The sandy-silty main seam parting of the eastern sub-basin includes only a few horizons with plant remains. Their investigation has not been completed yet. The species poor diaspore spectra may reflect riverside forests (*Sequoia, Nyssa, Cercidiphyllum, Rubus*) and includes herbaceous plants of the forest undergrowth and/or reed-like vegetation (*Saururus, Ranunculus*, Araceae). Only *Sparganium* occurs in a high percentage (approx. 24 %). Elements of mesophytic (hinterland) forests are almost lacking here.

A connection between the main partings of the eastern and western sub-basins has not been observed. Their positions at the western margin of the western sub-basin and at the eastern margin of the eastern sub-basin prevent any correlation.

3.4. Hanging Wall

The fluvial sediments of the hanging wall show characteristics of floodplain- and floodbasin deposits and crevasse- and levee sediments. Channel fill deposits alternating with overbank deposits are more dominant in the lowermost part of the profile (Text-Fig. 3 and HAAS, this vol., Text-Fig. 7).

A slight relief is characteristic for floodplains and results in the formation of floodbasins which are still under water influence during relatively dry periods. In the Oberdorf area, these shallow lacustrine basins acted as fossil traps in which animal and plant remains from the reworked floodplain accumulated. Moreover, peat accumulated in these basins. Palaeosols occur frequently and are characterized by red earth layers, or bluish-greenish, siderite-bearing horizons indicative of waterlogged soils in swampy areas.

Crevasse splay sediments within the hanging wall profile indicate constant changes of erosional and accumulating processes within the floodplain. These processes are related to the formation of shallow depressions and elevations which are characterized by distinct floral and faunal compositions.

Compared to the sediments of the footwall and the main parting the heavy mineral distribution clearly shows a change from a low-grade metamorphic source area to a medium-grade metamorphic hinterland (Middle Austroalpine) resulting in a characteristic garnet-green hornblende-staurolite-zoisite assemblage.

The coaly layers within the hanging wall sediments are even more sulphur-rich than the main seam indicating neutral or even slightly basic pH-conditions. Obviously, the latter promoted the preservation of primary carbonate components, vertebrates and terrestrial/limnic snails which would be decomposed in an acidic environment.

The floristic composition of the hanging wall sediments documents mainly riverside and floodplain forests. Coaly, clayey, silty, marly or sandy layers include similar plant assemblages, with variable taxa percentages originating from fluviatile-lacustrine environments. The leaf spectra of the silty-clayey horizons consist of *Glyptostrobus* and/or *Sequoia, Cercidiphyllum, Fraxinus, Alnus, Salix, Acer, and Zelkova*. *Quercus rhenana*, the characteristic element of swamp forest habitats, has not been discovered here. Some of the cited genera are also represented by diaspores (*Glyptostrobus, Sequoia, Cercidiphyllum, Fraxinus*, and *Alnus*). Additional elements in the diaspore record from these layers are *Meliosma, Nyssa, Liquidambar, Celtis, Prunus, Myrica, Eurya*, ? *Cleyera, Decodon*. Sometimes the latter is represented by higher percentages than in any other part of the lignite-bearing sequence in Oberdorf. The occurrence of *Potamogeton* and the Charophyceae *Lychnothamnus* in other layers indicates that small lacustrine habitats developed. Elements of mesophytic (hinterland) forests are almost lacking in the leaf record. They are documented in the diaspore spectra of sandy lenses or layers e.g. *Fagus, Mastixia, Symplocos, Toddalia*. Again, they are less well represented than in the sediments from the top of the footwall and the base of the seam.

Palaeozoological investigations gave evidence of two fossil-rich horizons which are concentrated at the basal parts of two lignite-bearing layers (Text-Fig. 3 and DAXNER-HÖCK, this vol.). Although different in abundance of specimens, both fossil layers show almost equal species contents representing the same stage of evolution. Therefore, both faunas are considered to be essentially coeval and are treated as one unit. The vertebrate fauna is rich in amphibians, lizards, snakes and small mammals, while large mammals and birds are each represented by a few fossils.

The very diverse amphibian and reptile faunas are represented by rich fossil materials including jaws and postcranial elements. On the other hand, 56 mammal species are recorded almost exclusively by isolated teeth and a few jaws; no skulls or articulated skeletons were found. This selection, deposition and concentration of isolated remains of vertebrates, which originally inhabited various biotopes, is interpreted to be a result of different taphonomic processes.

88 % of the mammal species belong to small mammals. Among them marsupials, chiropters and lagomorphs occur sporadically, but rodents and insectivores dominate with approximately 20 species each. The majority of them lived in burrows, or in bushes, under rotting logs or fallen

trees. We assume that tree squirrels, flying squirrels and dormice were arboricolous, using hollow trees for shelter and for their nests, as their extant relatives do. The flying squirrels, which are represented by three species, need high trees for gliding from one tree to the next. Although partly omnivorous or insectivorous most of the observed small mammals were plant eaters, using the forest for living and its rich supply of fruits, berries, seeds, nuts, twigs, leaves and roots for food. The variety of snakes, lizards and amphibians, including Caudata and Anura, fit in a forest environment as well. There is no record of any inhabitant of open country, except for a few teeth of a lagomorph and these have been interpreted as prey relicts.

The large mammal association consists of cervids, tragulids and one species of rhino and pig. All of them require forest biotopes and we assume that they would also accept a swampy environment close to a river system. Gastropods have been collected from several horizons of the hanging wall but their study remains to be completed.

4. Palaeoenvironmental Reconstruction of the Western Sub-Basin by Palaeobotanical Analyses

The refilling of this sub-basin has hindered its sedimentological investigation. In the leaf and diaspore assemblages of the coarse-grained fluviatile sediments of the main seam parting, elements of riverside forests are dominant. The species-poor leaf spectra include *Salix* (often dominant), *Cephalotaxus, Sequoia, Cercidiphyllum*, *Myrica* and ? *Gordonia*. The diaspores are often poorly preserved and represent riverside facies as well (e.g. *Sequoia, Glyptostrobus, Cephalotaxus, Alnus, Actinidia, Carya, Prunus, Pterocarya, Magnolia, Eurya, Sambucus, Rubus*). Mesophytic (hinterland) forests are documented by *Mastixia*, cf. *Trigonobalanopsis, Symplocos, Ternstroemia, Fagus, Meliosma pliocaenica*, cf. *Zanthoxylum*, cf. *Toddalia*, and others.

However, the diaspore and leaf spectra are species-poor in comparison to the footwall sediments in the eastern sub-basin. In the leaf spectra, mesophytic elements are completely lacking and in the diaspore record they are only represented by few specimens or fragments. Elements indicative of swamp habitats are dominant in clayey facies only (e.g. *Quercus rhenana, Glyptostrobus europaeus* KOVAR-EDER & MELLER, in press).

5. Palaeoclimate

Living relatives of the detected evergreen and deciduous genera and comparable associations have been described from the southern area of the Mixed Mesophytic Forests (MMF) and the northern as well as mountaneous regions of the Evergreen Broad-Leaved Forests (EB-LF) in China (WANG, 1961) and Japan (KLÖTZLI, 1988), where these forest types are mixed. Although richer in species than the fossil assemblages, they seem to be the nearest living equivalents. The mean annual temperature (MAT) in the MMF is between 11 and 16°C, the mean annual precipitation (MAP) between 1000–2000 mm, and in the EB-LF 15 and 20°C and 1280–2000(–3000) mm (KLÖTZLI, 1988; WANG, 1961). Therefore, the palaeoclimatic conditions may be estimated at 14–17°C MAT and 1000–2000 mm MAP.

6. Conclusions

Basin formation and coal deposition in the Early Miocene Köflach/Voitsberg Formation was controlled by NE–SW-directed extension and normal faulting, which led to the formation of shallow depressions along grabens or half grabens within a hilly lowland. These were filled with coal-bearing fluviatile and limnic sequences. The sedimentary facies provides evidence for temporarily occurring palaeosols comparable with present waterlogged surface water gleys. Red earth layers indicating palaeosol development under oxic conditions are also present but less frequent.

Summarizing the very detailed results of the different plant organ assemblages from all levels, lacustrine environments, reed facies, bogs, swamps, riverside forests and mesophytic (hinterland) forests are documented. At different levels and in relation to the depositional facies, the cited habitats are reflected to varying degrees. In addition, the taxa percentages also depend on the shifting of habitats and plant successions due to the evolution of the fluviatile and lacustrine system.

The forest and swamp biotopes offered optimal living conditions for amphibians, lizards, snakes and mammals.

The palaeoclimatic reconstruction based on the ratio of presumably deciduous versus evergreen plants points to warm-temperate sub-tropic and humid conditions.

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