

Miloš Marki & Reinhard F. Sachsenhofer

# THE VELENJE LIGNITE

## Its Petrology and Genesis



GEOLOŠKI ZAVOD SLOVENIJE  
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# THE VELENJE LIGNITE – ITS PETROLOGY AND GENESIS

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## Preface and acknowledgements

Petrological study of the Velenje lignite presented and discussed in this monograph started in 1992. It was initiated by Aleksander BREZIGAR and Dr. Bogomir JELEN, two excellent geologists working for the Geological Survey of Slovenia at that time. They informed the first author about a possibility to do systematic logging, petrographic description and sampling of lignite in the cores of boreholes P-8z/92, P-9k/92, and P-12o/92 situated in the northern marginal and central area of the Velenje basin. When this initial work was completed, Aleksander BREZIGAR organized a presentation of the study results at the Velenje Lignite Mine. On this basis, a long lasting and still ongoing cooperation with the colleagues at the coal mine, especially with Dr. Simon ZAVŠEK, was established. It also should be highlighted, that the petrological investigations during the whole duration of the project were financed exclusively by the Velenje Lignite Mine (VLM) led during the last twenty years by the following directors: Dr. Franc ŽERDIN, Dr. Evgen DERVARIČ and Dr. Milan MEDVED.

The first author worked many hours in the underground mine and spent a lot of time with geological investigations in the geomechanical laboratory of the VLM. We thank Janez JEZERŠEK and Edo BURICH, who led this laboratory, as well as the entire laboratory staff for their permanent assistance, taking care of safety, and enabling best possible working conditions, which contributed significantly to the success of this study. Sincere thanks are also given to groups of unnamed miners who transported hundreds of core boxes from the mine into the laboratory, thus providing ideal conditions for core logging and sampling. In this laboratory, also low temperature ashing of lignite samples was performed. We appreciate the great help of Mrs. Jožica ROUŠNIK, who did this work with great patience and accuracy.

The decision to restart petrological research of the Velenje lignite following Dr. Milan HAMRLA's pioneering studies in the 1950s was highly influenced by the work of Dr. Jože UHAN. In 1990 he, at that time also with the Geological Survey in Ljubljana, started to study the geochemistry of the Zasavje (Trbovlje) coal. The beginning of the 1990s was a time when coal exploration in Slovenia, which experienced its heydays in the 1980s, was in decline. Many geologists dealing with coal deposits finalised their studies and thereafter left this branch of geology. Thus Dr. Jože UHAN's initiative became decisive for the further development of coal geology in Slovenia.



Dr. Jože UHAN studied the Zasavje (Trbovlje) coal of Oligocene age in two representative seam sections, the Lopata and the Neža profiles. He started his work with macro-petrographic description of coal in terms of brown-coal lithotypes. His terminology followed the working recommendations (drafts) of the International Committee for Coal Petrology from the 1980s. A similar terminology was finally accepted by the International Committee for Coal and Organic Petrology in 1993 (e.g. TAYLOR et al., 1998 - tab 5.2). Thereafter, interval samples were taken considering the lithotype variability. Beside his main topic, i.e. geochemical characterization and interpretation of coal (UHAN, 1991, 1993, 1996), he initiated supplementary semi-quantitative palynological and micro-petrographical studies of the coal. One of the main results was the discovery that coal can be clearly separated into several geochemically, palynologically and petrographically coinciding units (MARKIČ et al., 1993), each of them being a result of specific peat-forming environments and subsequent diagenetic processes. Ten years later, the analyses of biomarkers and of carbon isotopes of the organic matter were added to the existing geochemical, paleobotanical and petrographical data for the Zasavje (Trbovlje) coal in the Neža profile (BECHTEL et al., 2004).

In 1996, a regional palynological research of the Oligocene beds in the Gornji Grad and the Hrastnik area was carried out by Dr. Angela BRUCH from the Institute and Museum for Geology and Paleontology of the Tübingen University (BRUCH, 1998). Besides quantitative floristic analysis (altogether she identified 141 taxa of pollen and spores), her study was targeted to the reconstruction of paleoenvironment and paleoclimate in the Eastern Alpine realm. At Hrastnik, she studied pollen taxa from coal samples from the Zasavje coal seam in the Ojstro OjL6/96 profile. One of the main achievements of BRUCH's study has been the determination of mean seasonal temperatures (e.g. 16–19 °C as a mean annual temperature during peat deposition) using the coexistence approach (MOSBRUGGER & UTESCHER, 1997). The palynological survey of the OjL6/96 profile was complemented by petrographic investigations performed by the first author. Using the “hard coal” lithotype terminology after Stopes (1919) (e.g. TAYLOR et al. 1998 - tab 5.1), the coal was described as an alternation of relatively thick bands of bright coal (vitrain), dull coal (durain), thinly layered bright and dull coal (clarain), and of char-coal (fusain). This approach was applied (tested) because the Zasavje coal is a relatively high-rank “brown coal”. From similar reasons, in a following study on the sedimentological characteristics of the coal-bearing Trbovlje beds by HAFNER (2000), the “hard coal” lithotype terminology was used, this time applying the “Australian” lithotype classification after DIESSEL (1965) (in BUSTIN et al., 1985).

In 1995, on the initiative of Doc. Dr. Dragomir SKABERNE and Dr. Bogomir JELEN, a long lasting cooperation between the authors of this monograph commenced. The first author spent three months at the Institute of Geosciences – Mining University of Leoben (Austria) within the frame of an Alpe-Adria scholarship. Here, he studied the micro-petrography of lignite from the Velenje basin on the basis of the representative P-9k/92 and P-87/92 seam profiles (MARKIČ and SACHSENHOFER, 1997). The authors highly appreciate the financial support of this cooperation by the government of Styria. The authors thank also Mr. Janez TOMŠIČ, the

director of the Geological Survey in Ljubljana in the mid of 1990s, for this cooperation and understanding. The great personal and professional help by Prof. Dr. Fritz EBNER, the head of the Institute of Geosciences (Mining University Leoben) at the time, created a very stimulating working atmosphere, which contributed decisively to productive cooperation.

At the end of the 1990s, Prof. Dr. Jože PEZDIČ from the Department of Geology - University of Ljubljana started a research project entitled “Origin, transport and accumulation of gases in the Velenje lignite”. Thus, beside the use of lignite petrography in geo-mechanics (as initiated by Dr. Simon ZAVŠEK), gas had become a new field for applied petrographical investigations. Prof. PEZDIČ also initiated isotopic investigations, which then flourished by the research of Dr. Tjaša KANDUČ. To all three of them, Prof. Dr. Jože PEZDIČ, Dr. Simon ZAVŠEK and Dr. Tjaša KANDUČ, we express our sincere respect and thank for realizing the potential of petrographical characterization in the frame of their studies. In this way, they contributed immensely to the development of applied coal petrology in Velenje.

The cooperation between the authors of the monograph commenced in the mid-1990s and resulted in cordial friendship. Apart from this, the cooperation brought together scientists with complementary research interests. Whereas the first author is an expert for Slovenian coal geology and the application of coal petrography in mining, the second author is an expert for coal in Alpine regimes and the relation between basin evolution and coal formation. Obviously the results obtained in Eastern Alpine coal basins SACHSENHOFER, 2000; SACHSENHOFER et al., 2000-a, -b, 2003; GRUBER & SACHSENHOFER, 2001; GRUBER et al., 2003; BECHTEL et al., 2007-a, -b) strongly stimulated research in Slovenian basins and vice versa.

The first author would like to specially highlight that his decision to devote his career mainly to coal geology and petrology was born as early as in his student years. Among the professors at the Department of Geology – University of Ljubljana, Acad. Prof. Dr. Matija DROVENIK influenced decisively his interest in coal petrology. Prof. Matija DROVENIK is not only an excellent professor of ore microscopy, with the emphasis on ore genesis, but he also gave to his students very well prepared lectures on coal geology and coal petrology, as well as practical exercises in coal microscopy. With his wide knowledge, enthusiasm and devotion to teaching he educated many generations of students of geology and mining in Ljubljana.

In addition, the first author would like to emphasize that he had the great luck to begin his career in the 1980s at the Geological Survey in Ljubljana – Department of Economic Geology in the team of so great geologists as Karel GRAD, Marijan MARIN, Dr. Ladislav PLACER, Ivan STRGAR, and Rajko PETRICA. These were the heydays of coal exploration in Slovenia, and the mentioned mentors and colleagues were always open for geological discussions, commentaries and supervisions. Great thanks to all of them for a highly stimulating atmosphere as well as for their personal heartiness.

During long lasting studies in Velenje, Dr. Slavko ŠOLAR, Doc. Dr. Dragomir SKABERNE, and MSc. Duška ROKAVEC were the heads of the Department of Economic Geology, and the following directors of the Geological Survey of Slovenia officiated during this time: Avgust ČEBULJ, Janez TOMŠIČ, Trajan DIMKOVSKI, Prof. Dr. Bojan OGORELEC, and Doc. Dr. Marko KOMAC. Most of them were to a greater or smaller extent also engaged in coal geology and followed the work presented in this monograph with personal interest and professional support. Conditions at the Geological Survey of Slovenia to write this monograph were almost ideal.

Many sketches, maps and diagrams in this monograph were improved and finalised by technical assistants at the Geological Survey of Slovenia: Vida PAVLICA, Jože ŠTIH, and Duška ŽIVANOVIĆ. Samples for XRD and geochemical analyses were carefully prepared by Štefica ŠTEFANEC and Mladen ŠTUMERGAR.

One of the fundamental approaches in the study of the Velenje lignite was to use sedimentological principles in the macro-petrographical description of lignite. Finally this resulted in a new lithotype classification. This approach was significantly influenced by Doc. Dr. Dragomir SKABERNE, a sedimentary geologist who accompanied the work of the first author for almost thirty years. His papers on the classification and nomenclature of clastic sediments (SKABERNE, 1980-a, -b) are undoubtedly among the best contributions in this field in Slovenia. Many discussions with him, ideas and suggestions contributed a lot to this monograph.

In the field of tectonic geology, instructions and explanations of Dr. Ladislav PLACER helped a lot to clarify different tectonic effects during mapping in the Velenje underground workings. He also reviewed numerous reports and papers written by the first author. So, many thanks go to Dr. Ladislav PLACER for all his advices, critical comments, and encouragements.

Finally, we are both especially thankful to our families, dear wives and children for their every day source of energy and happiness, as well as to our teachers, colleagues and friends.

Ljubljana, Leoben, May 2010

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Reinhard F. Sachsenhofer

## Abstract

This monograph presents and discusses results of petrological studies of lignite in the Velenje basin, which were performed during more than 15 years. The Velenje basin is a tectonically controlled intermountain basin filled by a succession of Pliocene to Plio-Quaternary sediments, more than 1000 m thick. The main lignite seam is located in the middle part of the Neogene succession and forms a bowl-shaped mega-lens. The lignite seam is approximately 8.3 km long, 1.5–2.5 km wide and on average 60 m thick. In a considerable part its thickness exceeds 100 m and may even reach 165 m. The low rank of the lignite (ortho-lignite) is reflected by a strong petrological heterogeneity, which is a challenge for fundamental studies as well as the source of highly variable geotechnical properties and behaviour in the underground mine.

The main topics of this monograph are the petrographical and geochemical characterization of the lignite. Lignite petrography was studied from macro- to micro-levels, in a wide range of dimensions, ranging from meter/centimeter-scale applicable in geological mapping of lignite in the underground mine workings and borehole cores, to micrometer-scale in the case of micro-petrography (reflected-light microscopy) and scanning electron microscopy.

Macro-petrographical studies in the underground mine workings documented a zonation of lignite facies, changing from xylite-rich (forest swamp) facies characteristic for the outer and the lower part of the lignite seam, to fine detrital (open-water surfaces with dwarf plant vegetation or fen) facies predominating in the inner and the upper part of the seam.

A similar, but more diverse trend was also revealed by a systematic quantitative maceral analysis along the lignite seam profile in the P-9k/92 core-drilled borehole in the central part of the lignite seam. In addition, borehole P-8z/92 situated near the northern margin of the lignite seam was also studied to determine facies changes between the periphery and the centre of the lignite seam. (Paleo)peat-forming environments were interpreted by the use of so called DIESSEL's petrographic indices (tissue preservation index - TPI and gelification index - GI). In the reference P-9k/92 borehole, the lignite seam was divided into three main units, which were further subdivided into up to three subunits. The units and subunits (labelled from bottom to top of the seam as I, II-a,b,c and III-a,b) were interpreted as the following peat forming environments: wet forest swamp, dry forest swamp, bush moor, wet forest swamp and fen.

Petrography of lignite in borehole cores involved more than 2.500 metres, but majority (73) of these boreholes were “technical”, close-to horizontally drilled underground boreholes. Only four boreholes, of a total length 285 m of cored lignite, were drilled from the surface perpendicular through the lignite seam.



In the frame of the underground mapping, more than 200 road-faces were documented petrographically and structurally. Long-walls were mapped to a much lower extent, because of difficult working conditions.

A new macro-petrographic classification for low-rank coals (lignites) is proposed in this monograph. The need for a new macro-petrographic classification arose from the fact that the existing lithotype classification (ICCP, 1993 – in TAYLOR et al., 1998, p.280) was not satisfactory to characterize the lignite for different purposes, ranging from fundamental petrography to applied tasks, e.g. lithotype characterization of samples for geo-mechanical, petrophysical, and gas dynamical investigations. In order to follow existing classifications and criteria, the concept of the UDEN scale as conceptually used for clastic sediments was introduced in the petrography of lignite. In description of fragmental patterns of lignite, the concept of lithotype components was applied, differentiating between the following components: Detrite (D – composed of detritus <1 mm), xylo-Detrite (xD – composed of 1–32 mm big xylite pieces and the surrounding fine detrital matrix), detro-Xylite (composed of 32–64 mm big xylite pieces and the surrounding fine detrital matrix), and Xlite including lumps (X), branches/stumps (XX) and trunks (XXX) in dimensional intervals 64–512 mm, 512–2048 mm and >2048 mm. Quantitatively, the so called 10 % rule from the ICCP (1993) classification was replaced by classes with 0–15, 15–40, 40–60, 60–85 and 85–100 %, which are similar to those used for lithotype petrography of bituminous coals. Finally, a codification system was established for easier data management and communication with results of other (non-petrographic) investigations.

Inorganic geochemical analysis of lignite was performed throughout the P-9k/92 core profile. It involved 30 lignite samples, and 9 samples from the floor and roof sediments. Apart from the main coal elements C and S, eleven minor (mineral-forming) elements (expressed in the form of oxides) were analyzed together with 46 trace elements. In order to avoid thermal effects due to high temperature ashing, analytical samples were whole coals. Despite of this, the concentrations of only few elements (Ni, Hf, Sn, Ta, Cd, Ag, Au, Tl and Se) were beyond the detection limits in a considerable number of samples. It was found out (by recalculation to the dry, organic matter free basis) that inorganic matter of the lignite is highly characterized by the following composition: SiO<sub>2</sub> (20–52 %), Al<sub>2</sub>O<sub>3</sub> (15–29 %), Fe<sub>2</sub>O<sub>3</sub> (6–24 %), and CaO (2–34 %). Contents of the cited element oxides significantly depend on the inorganic matter yield with an interesting threshold at 20–25 % ash yield. Typical mineral matter forming oxides SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> (in close correlation;  $r^2 = 0.92$ ) increase (as a sum) up to the mentioned threshold at 20–25 % ash yield from 40 to 80 % and are relatively constant (80–85 %) above the threshold. On the contrary, CaO, MgO, and Fe<sub>2</sub>O<sub>3</sub> contents are high in samples with ash yields below 20–25 %. Because of this fact and due to low portions of inorganic carbon, it is concluded that Ca, Mg, and possibly also Fe are mostly organically bound elements.

The greater part of trace elements analyzed in the Velenje lignite is within normal limits in comparison to world coals. Higher than normal are contents of U (5–15 ppm – in comparison to 0.5–10 ppm contents in world coals), and of Mo (5–20 ppm – in comparison to 0.1–10 ppm in world coals). Both elements are presumed to be, at least partially, organically bound.

Mineralogical XRD investigations on ashes revealed that “moderate”-temperature (ca. 400 °C) ashing yields good material for such analyses, whereas whole coals are mostly too amorphous to show interpretative XRD spectra. Very low contents in mineral-matter-forming elements apart from Si and Al (noting that Ca, Mg and Fe are to a great part organically bound) suggest that, beside quartz, more or less “pure” aluminosilicates form the clay minerals

in the Velenje lignite. Indeed, kaolinite was ascertained in most investigated samples as predominating over illite.

The lignite seam formed in the intermountain Velenje pull-apart basin. This basin type is characterized by very high subsidence rates, which control basin architecture and peat forming environments. During early stages of basin formation, the Velenje basin was filled with fluvial sediments. Because subsidence exceeded sediment input, the fluvial environment was replaced by a lacustrine one. The Velenje seam formed during the transition from the fluvial to the lacustrine environment. The petrographic composition reflects deposition in a low-lying, eutrophic, and Ca-rich mire and a continuous rise of relative water level during peat accumulation. Whereas the ash-rich lower part of the lignite seam is still strongly influenced by fluvial processes, the low-ash upper part has been mainly influenced by lacustrine processes. A general decrease in the abundance of xylitic coal from bottom to top suggests a vegetation rich in trees during accumulation of the fluvial-controlled lower part of the seam and a prevalence of bush and reed vegetation during deposition of the upper part of the seam. Peat accumulation was terminated by a rapid relative rise in water (lake) level. After the termination of peat accumulation, lacustrine environments prevailed in the Velenje basin. At least one additional lignite seam occurs in the Velenje basin far above the main lignite seam. Although detailed description of the geology of the high-ash lignite is not available, it is likely, that this seam formed during the filling stage of the lake, which formed after accumulation of the main seam, in a deltaic environment. Limited thickness and lateral extension are typical for this type of coal, which formed in a regressive setting.

The Ca-rich geochemical character, especially prominent at the northern margin of the seam due to a Triassic dolostone and limestone hinterland, caused alkaline conditions. It is presumed that alkalinity gradually increased from the bottom toward the top of the seam. A well known relation between alkalinity and gelification was clearly ascertained in the case of the Velenje lignite. Lignite samples with the highest calcium contents were also the samples with the strongest gelification. Furthermore, lignite in the P-8z/92 borehole (where the lignite is close to Triassic carbonates), was identified to be considerably stronger gelified than in the central part of the basin. In addition, both Ca (and Mg) content and the degree of gelification (quantified by GI) show an upward increasing trend. On the other hand, a close correlation between sulphur content and gelification was not found, even though the sulphur content is generally (moderate to) high (1–5 %, dry basis), and thus supporting interpretation of a relatively alkaline depositional environment of the peat/lignite formation.

Interesting correlations, but also “non-correlations” were found between the degree of gelification and ash yield implying that different factors could govern plant (wood) degradation and gelification processes. In units II (dry forest swamp and bush moor) and III (wet forest swamp and fen) as defined in the central part of the lignite seam (P-9k/92), gelification index increases with decreasing ash yield. On the contrary, in the lowermost unit I in the central part of the basin (P-9k/92) and in the northern marginal part of the lignite seam, which are both mineral-rich, gelification is also considerably high. In the first case, relatively aerobic conditions are presumed to be decisive for the initial vegetal decomposition (occurrence of textinites B and rare siderite) which were later replaced by more anaerobic conditions due to a water table rise and hence activity of anaerobic bacteria, which accelerated biochemical gelification processes. In the second case, alkalinity, consequentially enhanced bacterial activity and enhanced biochemical gelification were caused by both, vicinity of carbonates in the hinterland, and by detrital sediments of predominantly carbonate character. Mixing of ground-water inflows and incoming mineral matter, in some periods more intensive

from the southern, prevailing Oligocene andesitic terrains, and in other periods from northern, prevailing Triassic carbonate terrains, played an important role in geochemical characteristics of waters that percolated through the peat/lignite. Based on geochemical data, it is presumed that mineral matter input in the initial stage of the peat formation in a low-lying (topogeneous) mire environment was mainly from the southern Si-Al dominated andesitic (easily weathered) hinterland, whereas the continuation of peat formation was gradually more and more influenced by lacustrine waters from the north and diminished mineral matter influx.

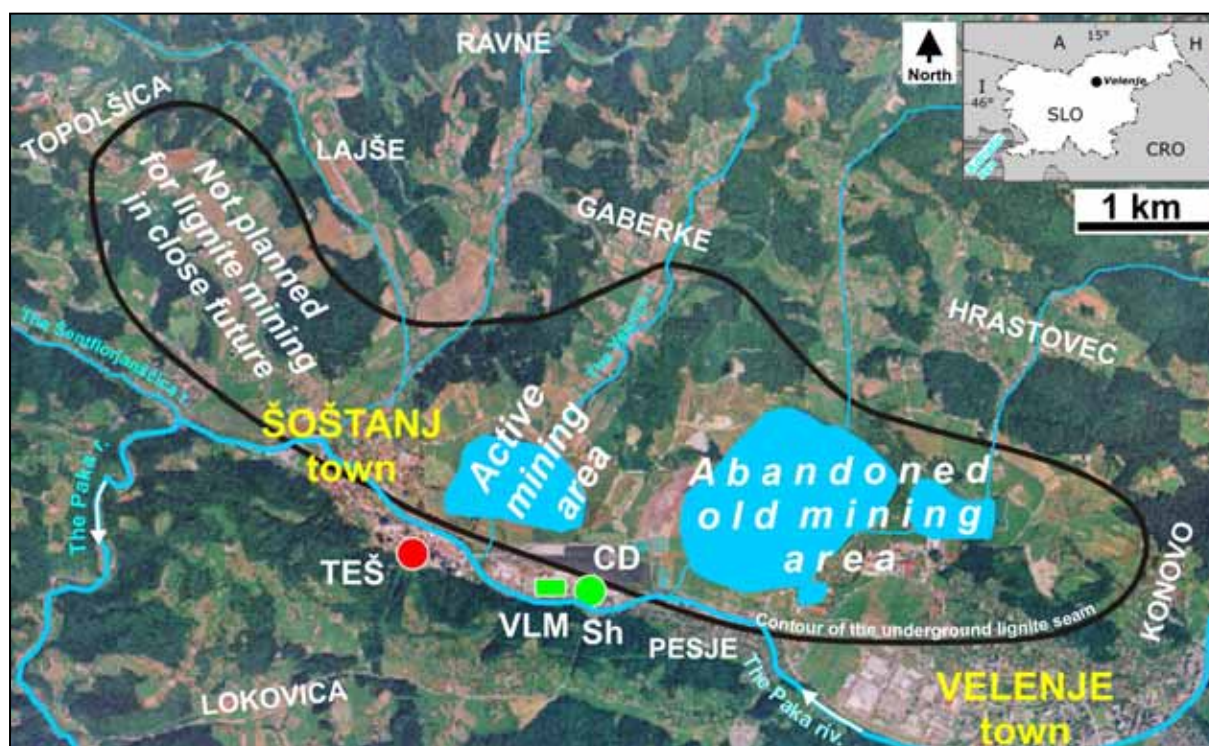
It can be concluded that lignite petrography and geochemistry, together with a range of additional investigations, which were performed by colleagues (palynology, organic geochemistry, isotopic geochemistry, mineralogy) contributed significantly to the understanding of the Velenje lignite.

This monograph would like to show the great importance of coal petrography for both, fundamental and practical aspects of coal geology. It is the aim of the authors to combine both. This is because the value of fundamental studies is increased, if the results can be checked and controlled in praxis, and, vice versa, practical work is of short breath if not supported by basic research.

# 1. INTRODUCTION

## 1.1. Geographical and basic geological background

The Velenje lignite deposit is named after the town of Velenje in N Slovenia. Today Velenje is the fifth largest town in the country (about 28.000 inhabitants), but was only a small village before coal mining in the Šalek valley (**Fig. 1.1**) began to expand rapidly after 1950. At present, modern underground exploitation carried out by the Velenje Lignite Mine (VLM) amounts to a lignite production of ca. 4 Mt/a<sup>1</sup>. The lignite is of Pliocene age. In recent years its calorific value has varied around 10.3 ( $\pm 0.2$ ) MJ/kg (“as delivered basis”). Almost the entire lignite production is consumed by the thermal power plant (755 MW)<sup>2</sup> situated in Šoštanj. The power plant (**Fig. 1.2**) is directly connected to the mine, and produces about 33 % of domestic electricity. The whole system represents the greatest energy-production site in Slovenia (MOPE-RS, 2001; ŽERDIN, 2003; TEŠ, 2005).



**Fig. 1.1:** Geography of the Velenje – Šoštanj area. The black elliptical line outlines the lignite seam in the subsurface. Due to surface subsidence, wide lakes formed above abandoned and present underground mining activity. TEŠ – thermal power plant; VLM – Velenje lignite mine (direction building); Sh – the main shaft; CD – coal depot. (Adopted after VEBER & DERVARIC, 2004).

**Note:** For this figure to be seen in colours the reader is referred to <http://www.geo-zs.si> – the same is true for many other figures in this monograph).

<sup>1</sup> ca. - circa, about; Mt: mega-ton –  $10^6$  tons; a - year

<sup>2</sup> 755 MW (mega-watt) is power of the generators installed at the present





**Fig. 1.2:** *a) The main shaft (Sh in Fig. 1.1) of the Velenje Lignite Mine and the Uršlja gora mountain (1700 m a.s.l.) in the far back - 16 km to the north. b) The Šoštanj Thermal Power Plant (TEŠ in Fig. 1.1) – note the coal conveyor coming from the right. In the lower left corner spruce (pine) forest covers an area built up of andesitic volcanoclastics south of the Šoštanj fault. Spruce is termed “smreka” in Slovenian, and the centre of the andesitic volcanism is termed Smrekovec. Direction of view is toward west.*

After closure of all traditional ore and coal mines in Slovenia – the Trbovlje-Hrastnik Coal Mine in the Zasavje region (central Slovenia) will stop its intensive, more than 200-year long coal production most probably in the close future – the Velenje Lignite Mine will remain the only active mine in Slovenia. With regard to its proven lignite reserves (VEBER, 1999), the needs of domestic energy production/consumption, and taking into account the complex political, economical, technological and environmental principles of modern mining and sustainable development, it will operate almost undoubtedly in the next decades (ŽERDIN, 2003; MOPE-RS, 2003; DERVARIČ & MALENKOVIĆ, 2005).

The distance between the towns of Velenje and Šoštanj is less than 5 km. The latter is much smaller but historically more significant. Both towns are well connected and economically highly developed centres of the Šalek valley, the heart of the Velenje depression. The moderately undulating land surface of the valley at 350 to 400 m a.s.l.<sup>3</sup> is surrounded by a hilly hinterland of the Velenje depression with the highest peaks and crests as high as almost 1600 m a.s.l. to the W<sup>4</sup> (Golte and Smrekovec), 850 m a.s.l. to the N (Graška gora), close to 1300 m a.s.l. to the E (Paški Kozjak), and between 450 and 550 m a.s.l. to the S (Lokovica and Ložnice). Western and northern mountainous regions belong to the Kamnik-Savinja Alps (easternmost part of the Southern Calcareous Alps) and to the Karavanke Mountains, respectively. The hilly area to the south and south-east separates the Velenje depression from the Celje depression. The climate is humid, typical of the Alpine foothills, with a slight continental influence from the Pannonian lowland in the east (Es, 1999).

<sup>3</sup> a.s.l. – above sea level

<sup>4</sup> Abbreviations N, S, W, E (and combinations) will be mostly used for north, south, west and east

Surface hydrology of the Šalek valley is balanced by the relatively small river Paka with the Velunja and the Šentflorjanščica rivulets as its main tributaries. Much more outstanding are the three so called Šalek lakes formed due to underground mining. At present, they cover in total a surface area of 2 km<sup>2</sup>, and contain more than 40 Mm<sup>3</sup> of water<sup>5</sup>. Two lakes are very deep, 55 and 75 m respectively. The total due-to-mining subsided area (6 km<sup>2</sup>) and volume (110 Mm<sup>3</sup>) are even three times larger. Alkalinity of the lake water due to ash disposal from the power plant was a major problem for years. Before 1991, its pH values ranged between 11 and 12. After changing the technology of ash disposal into closed ash-bearing water circle, alkalinity dropped below pH 9 (ŠTERBENK, 1999; ŠTERBENK & RAMŠAK, 1999; ZRC-SAZU, 2005). As it will be discussed later, carbonate, especially the Ca-rich character of the mineral matter (ash) of the lignite exploited, is to a great part responsible for the mentioned alkalinity.

The landscape above the underground lignite mine between Velenje and Šoštanj, including not only subsided areas but also vanished small villages, now represents the largest man-transformed land-surface in Slovenia (ES, 1999).

Forestry, agriculture (mostly for domestic use), tourism, small-size enterprises and trade are the main economic branches in the hilly areas. Beside the Velenje Lignite Mine and the Šoštanj Thermal Power Plant, other industrial activities are also concentrated in the Šalek valley, such as the well known industry of domestic appliances Gorenje, a construction company Vegrad, small textile industry, plastics production and some other diverse activities of social interest. Two dolomite and limestone quarries, providing raw material for construction, operate in the Paka gorge north of Velenje (ES, 1999).

The contrast-rich topography of the area, including deep valleys and high mountains, indicates that young to recent geological processes played a significant role in the shaping of the relief. Two geographical features are especially important to a geologist, – a sharp NW–SE topographic line along the SW margin of the Šalek valley, and a prominent change in the flow direction of the Paka river along this line (**Fig. 1.3**).

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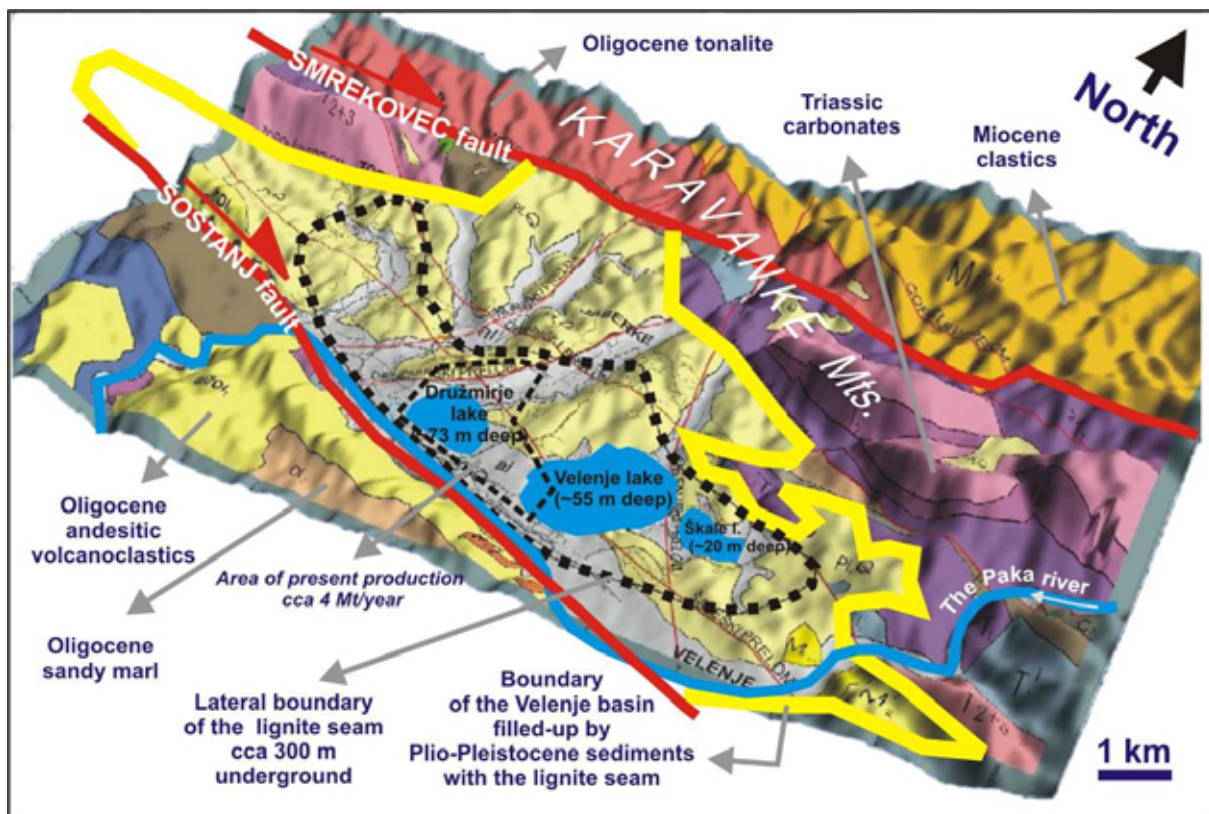
The geology of the area will be presented in more detail in a separate chapter, but some basic information (mainly after MIOČ & ŽNIDARČIČ, 1978, 1983; BREZIGAR, 1985/86) is given here for easier understanding (**Figs. 1.3 to 1.5**).

The mentioned spectacular topographic line is geologically referred to as the Šoštanj fault, which is still active. The length of the section where the river Paka follows tightly the Šoštanj fault is 7 km (**Fig. 1.3**). This length gives some indications of the amount of lateral movement along the fault. The Šoštanj fault together with the northern Smrekovec fault forms part of the Periadriatic fault system, separating the Eastern Alps to the north and the Southern Alps (Dinarides) to the south.

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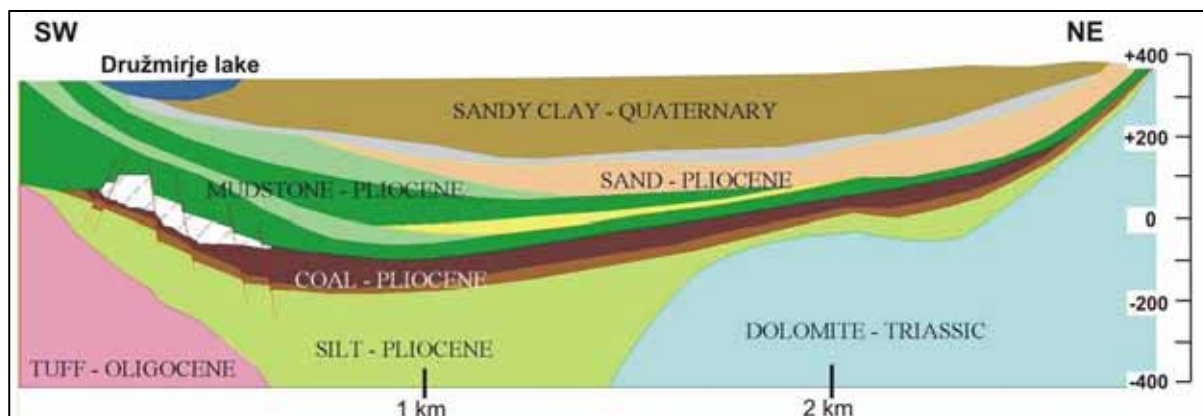
<sup>5</sup> Mm<sup>3</sup> – mega cubic metre – 10<sup>6</sup> cubic metres

The formation of the tectonically formed intermountain Velenje basin<sup>6</sup> and the evolution of accommodation space were largely controlled by movements along the Periadriatic fault system. The basin was filled during Pliocene and Plio-Pleistocene times by a succession of heterogeneous clastic sediments more than 1000 m thick. The Velenje lignite seam is embedded approximately in the middle of the Plio-Pleistocene succession. In the central part, the lignite seam is up to 165 m thick, whereas it pinches out towards the margins. The seam extends in the WNW–ESE direction in a length of 8.3 km and a width between 1.5 and 2.5 km. Bedding planes are nearly horizontal or slightly inclined. A second, minor seam occurs near the top of the Plio-Pleistocene succession.

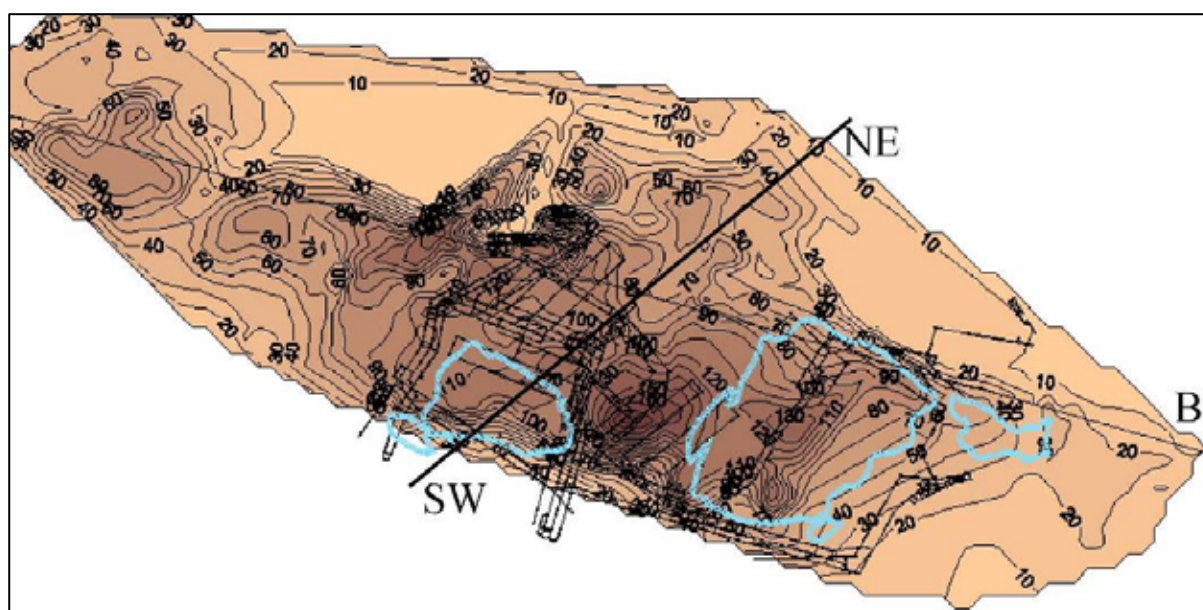


**Fig. 1.3:** General geology of the Velenje basin, compiled from the following sources: geology from MIOČ & ŽNIDARČIČ, 1976, 1981; compilation between topography (Geodetic Survey of Slovenia) and geology from VEGER & DERVARIČ, 2004). Note the stream course of the Pakar river, which follows the Šoštanj fault along a 7 km long segment.

<sup>6</sup> The term Velenje basin will be used in the following in a strictly geological sense, whereas the terms Šalek valley and Velenje depression are used in a geographical sense. In older German-language literature, the Velenje basin is termed Schönstein Becken. Note that Schönstein and Wöllan are the German names for Šoštanj and Velenje, respectively.



**Fig.1.4:** Schematic SW-NE trending geological cross-section (see Fig. 1.5 for the position of the profile) (from VEGER & DERVARIČ, 2004). Note the low distance between Triassic dolomite and the lignite seam along the northeastern, and between Oligocene andesitic tuff and the lignite seam along the southwestern segment.



**Fig.1.5:** Map of lignite thickness based on borehole data (from VEGER & DERVARIČ, 2004). Marked are the cross-section from Fig. 1.4 and the subsidence lakes. Note the increasing thickness towards the south.



## 1.2. Discovery of coal in the Šalek valley

(Compiled mostly from BREZIGAR, 1985/86, 2007, and from SEHER, 1995)

The oldest data mentioning coal in the Šalek (Schönstein) valley date 240 years back, into the age of Enlightenment. At that time, the growing energy and charcoal demand caused extensive deforestation. Thus, the findings of coal throughout Europe started to be accepted as very welcome. Also in the monarchy of Austria, during the reign of Empress MARIA THERESIA, coal findings were highly appreciated and even rewarded.

Pater STEIZ and Ivan FUCHS were the first who reported on coal in the Šalek valley to the government of the province of Styria in Graz in 1766-67. Seventy years later, in 1835, lignite and marls with molluscs from the Šalek valley were described by the French geologist BOUÉ in his “Aperçu sur la constitution géologique des Provinces Illiriennes” published in the *Mémoires de la Société Géologique de France*. A first basic paper on the geology of the Šalek valley and the lignite was written by Friedrich ROLLE in 1860. It was entitled “Die Lignit Ablagerung des Beckens von Schönstein in Unter-Steiermark und ihre Fossilien”. ROLLE (1860) also produced the first geological map of the area, from which it is seen that at this time lignite was already excavated at a small scale at three outcrop localities in the eastern part of the valley: Pesje (Hunddorf), Konovo – Turn, and Hrastovec – Sv. Bric (see **Fig. 1.1** for localities). The most important locality was that at the Pesje village. Still today, the eastern active part of the lignite mine is named after that village. Lignite mining at Pesje started in 1829 by Anton B. BONAZZA, the owner of the ironworks in the Mislinja valley<sup>7</sup>. Production in the first year reached 38 t. Lignite was low-grade at all localities and only up to 2.5 m thick.

ROLLE (1860) recognised that the then known coal layers do not belong to the same seam. He found out that the “brown coal” at Pesje is younger than the “brown coal” at Konovo, which is younger than the “black coal” at Hrastovec. Due to the low grade of the lignite and low demand, excavation did not develop to a greater scale in those years.

A turning point in the history of lignite mining in Velenje happened in the 1870s. After having drilled some boreholes at the periphery of the Šalek valley mostly near the known outcrops at Pesje, where only few metres of a shallow, very low-grade lignite<sup>8</sup> were encountered, Franc MAGES (coming to Velenje from Eisenerz; Austria/Styria) decided to drill a borehole in the central part of the Šalek valley. This was borehole I/875 located about 500 m west of the Konovo – Turn outcrop. This borehole encountered a 37-m-thick lignite seam beneath a depth of 101 m. It was soon realized that this is the thickest lignite seam in the valley, nowadays termed as the main lignite seam of the Pliocene age.

A brief presentation of the geology and the lignite seam in the Šalek valley as known at the beginning of the 1920s is given in the chapter titled “Die pliocänen Kohlenlager zwischen Drau und Save” in a famous monograph “Kohlengeologie der Österreichischen Teilstaaten” published by Wilhelm PETRASCHECK in 1926/29. In this chapter, a short textual description (PETRASCHECK, 1926/29, p.343) is supplemented by a geological map of the Velenje basin “after RIEDEL and TELLER” and by a geological profile. The latter clearly shows the concave shape of the lignite seam. It is mentioned that the seam is “dirty” (“unrein”) at the bottom, cleaner in its

<sup>7</sup> The Mislinja valley is a neighbouring valley to the north of the Velenje depression; some years after 1829, Bonazza found coal also in the Mislinja valley at the Stari trg village.

<sup>8</sup> Drilling in the Šalek valley started in 1873 and the peripheral lignite at the Pesje locality was soon recognized as a lignite occurrence in the overlying sediments high above the main lignite seam.

upper part and towards the centre of the basin, and reaches a maximum thickness of 115 m in the centre of the basin.

Opening of the colliery by progressive mine workings, in principle by shafts from the surface to the lignite seam and by in-seam mining roads, will not be discussed here because it is beyond the scope of the present thesis. But one very interesting palaeontological discovery should be mentioned here: In 1887/88, when the first shaft was constructed, mammal bones were found in the clayey material 60 m below the surface (82 m above the lignite seam). The bones were collected by mining engineer RIEDEL and determined as *Tapirus hungaricus* by TELLER (1888), one of the most outstanding geologists in Vienna at the time. Additional findings of that time were mammal teeth, also determined by Friedrich TELLER as mastodon teeth. It took almost 80 years until the next spectacular discovery of mastodons in the clayey sediments lying above the lignite seam was made in 1964 during ground levelling works in the NE part of the mine concession area (Škale district). The bones were detected by bulldozer workers, who informed mining engineer Dušan PIPUŠ, at that time director of the mine. A group of young geologists (Katica DROBNE, Vida and Janez POHAR, Majda PRESTOR) from the Geological Institute at the University of Ljubljana, mentored by the great Slovenian palaeontologist Ivan RAKOVEC, made a detailed excavation of mammal remnants (DROBNE, 1967). The remnants of the mastodons were determined by RAKOVEC (1968) to belong to *Bunolophodon (Anancus) arvernensis* Croiz.et Job., and to *Zygolophodon borsoni* Hays.

At the beginning of lignite mine operation, two mining disasters happened in 1893, when 31 miners died in two gas explosions due to bad air ventilation and a low level of safety measures.

### **1.3. Production of lignite and electrical energy**

(Data gathered mostly from SEHER, 1995; MOPE-RS, 2001; TEŠ www, 2005)

After Franc MAGES, exploration of the lignite deposit was continued by Daniel LAPP. In 1914, lignite reserves were evaluated to be 50 Mt. Underground mine workings and technology would enable a production of 0.3 Mt/a. However, higher-grade “brown coals”, especially those from the traditional Zasavje coal mining region (Zagorje, Trbovlje, Hrastnik, Laško collieries) were much more attractive for consumption than the Velenje lignite. Therefore, production in Velenje did not exceed 0.24 Mt/a up to 1940.

The Second World War resulted in considerably intensified exploration of the lignite seam between 1941 and 1944. The greatest thickness of lignite, 98 m, was drilled by borehole 1/42. In order to answer the question whether there is more lignite under the main lignite seam, one of the deepest boreholes in the basin was drilled in 1943. This was the 869-m-deep borehole 9/43. No coal was found under the main seam, and the borehole even did not reach the pre-Tertiary basement of the basin. Other wells confirmed the presence of the main seam with a considerable thickness and acceptable quality to the west of the Šalek valley i.e. under the Šoštanj town. On the other hand, it was proved that lignite does not occur to the east, under the Velenje town.

In the times of socialist Yugoslavia characterized by an overall industrial growth and development (with all positive and negative impacts), lignite production began to increase rapidly after 1954 (0.9 Mt/a) and gained its maximum between 1981 and 1986 (5.0–5.1 Mt/a).

In the mid-1970s, the maximum thickness of lignite – ca. 165 m (reported somewhat diversely – see **Tab. 2.2**) – was drilled by borehole 12f/74 (BREZIGAR, 1985/86, p.328).

Decrease in production to ca. 4 Mt/a at the beginning of the 1990s was related to the Slovenian energy strategy to diminish the share of domestic coals in the energy supply of the country – mainly due to reasons such as relatively high price, low grade and negative environmental impacts. However, most probably domestic coal will continue to play a considerable role in the future, because Slovenia is highly dependent on the import of energy resources such as oil, gas and uranium.

The first thermal plant for electricity generation was built in 1914 to provide the mine's infrastructure (ventilation, transportation, pumps, cable-ways), which at the time operated on the basis of steam. The author of this idea was the already mentioned owner of the mine, Daniel LAPP, who unfortunately died in 1910. He was probably the first to realise that lignite – as a low-grade fuel, unattractive for marketing – would be best used if transformed to heat, generating electricity at a site close to the mine, and to distribute it regionally. His ideas were realized in 1927 and 1934 by the first two blocks (in total ca. 7 MW) of the Velenje Thermal Power Plant. Electricity power generation moved in 1956 close to the Šoštanj town, and the thermal plants have since that time been named as the TEŠ (**Fig. 1.2**). The five blocks (TEŠ I–V) operating at present with a total installed power of 755 MW were built before 1977 (and later modernized). Parallel to the electricity production, residential heating of the Šalek valley was developed from the 1960s onwards. In 2005, 3,640 GWh of electrical energy (33 % share in domestic electricity production) and 450 GWh of the heating energy were produced (TEŠ, 2005). Permanent technological reconstructions and improvements resulted on the one hand in an increase of energy production efficiency and on the other hand in a considerable decrease of environmentally critical emissions (SO<sub>x</sub>, NO<sub>x</sub>, and fly ash).

CO<sub>2</sub> emissions are now globally considered as the main problem of coal use (and of fossil fuels in general) and should be reduced in the future. As it is generally known, one way is a further increase in the efficiency of energy production per ton of coal, and another one – maybe – the capture and storage (sequestration) of CO<sub>2</sub> (by so called CCS technologies) “in deep geological layers” (saline aquifers, abandoned oil and gas fields, non-mineable coal seams – all in depths greater than 800 m). These are technological issues, but mankind should also spend more effort to decrease energy consumption.

#### **1.4. Historical attempts to convert lignite into products of higher quality and value** (Compiled from SEHER, 1995)

Attempts to transform low grade Velenje lignite into products of higher quality and market value comprised briquetting, separation of xylite, drying, dry distillation (production of semi-coke, coke, and organic chemicals), and gasification (production of gas, semi-coke, coke, and chemicals).

At the beginning of the 20<sup>th</sup> century, Daniel LAPP started to produce briquettes from pre-dried fine-crushed lignite, mostly from separated lignite that was looking “pure” (low in ash yield). Between 1901 and 1914 the production of briquettes with calorific value of about 17–18 MJ/kg ranged between 2.0 and 8.8 kt/a<sup>9</sup>, i.e. between 2 and 10 % of the total lignite

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<sup>9</sup> kt: kilo-ton – 10<sup>3</sup> tons

production at the time. However, when exposed to the air, briquettes disintegrated in few days. After several repeated attempts, finally in 1945, briquetting was concluded as an unsuccessful technology.

Petrological reasons for the low quality of briquettes were not clarified more thoroughly. Maybe the degree of gelification, which will be widely discussed in the petrographic description of the Velenje lignite, could be an important reason (as e.g. recently debated for lignite of the Lower Rhine Basin in Germany by NAETH et al. (2004)).

Separation of xylite (fossil wood) was carried out from the early days of the mine up to 1964. Amounts of separated xylite pieces ranged between 3 and 6 % of the whole raw lignite production. Marketing of xylite was undertaken because xylite is characterized by lower moisture content and ash yield than the fine-detrital (matrix) lignite (**Tab. 1.1**) (data compiled after PETRASCHECK (1926/29, p.345). SEHER (1995, p.354) emphasizes that these data represent the first analysis of the Velenje lignite made in July 1886 by the Austrian Geological Survey in Vienna.

**Tab. 1.1:** *An early analysis of the Velenje lignite (arranged from PETRASCHECK (1926/29, p.345; and from SEHER, 1995, p.354). The site of sampling is unknown (most probably from boreholes). Data refer to an air dried basis. For newer data see also Tab. 6.5.*

	C	H	O+N	Moist.	Ash	C	H	O+N
	<i>As received – air dry basis (%)</i>					<i>Dry, ash-free basis (%)</i>		
<b>Xylite</b>	46.42	4.78	31.52	15.70	1.58	56.13	5.78	38.12
<b>Detrital lignite</b>	44.51	3.51	17.76	25.26	8.96	67.64	5.33	27.00

First attempts of dry distillation of xylite date back to the years between 1892 and 1917. Between 1907 and 1914, when the whole lignite production varied between 80 and 140 kt/a, the production of semi-coke ranged between 30 and 215 t/a (i.e. about 0.1 % of the annual lignite production). Experiments of extracting benzol and toluol from xylite-derived tar were first carried out in Vienna in 1917.

The next campaign of dry distillation is known from 1927. It lasted only three months. Semi-coke was produced from xylite and whole lignite (probably from separated low-ash variety). 410 t of semi-coke and 65 t of tar were produced from 1.300 t of lignite (SEHER, 1995, p.361), but the two products were almost entirely rejected by the consumers due to bad quality.

In Yugoslavia, a great demand for coke arose in 1948, when the import of coke from the Soviet Union stopped suddenly due to the TITO – STALIN political conflict. The production, reserves and quality of domestic high-rank coals suitable for coaking were not able to provide enough coke for the needs of the growing heavy industry. Great efforts in coke production were therefore focused on low rank coals, abundant throughout Yugoslavia (PANTIĆ & NIKOLIĆ, 1973; DIMITRIJEVIĆ & NIKOLIĆ, 1980; DROVENIK, 1984; FINKELMAN et al., 2002; ERCEGOVAC et al., 2006). Promising results were first achieved in Belgrade, where a good-quality coke from the Kreka (Bosnia) lignite was produced. Consequently, 12 coke furnaces were built in Velenje in 1949. 5.270 t of semi-coke were produced during two years of operation. However, the only favourable results were obtained from pure xylite, yielding 81

%  $C_{fix}$ . Negative responses from consumers, environmental impact (smell), low efficiency (high costs) of xylite separation, all together resulting in an inadequate economic warranty, were the main reasons to abandon further attempts with coke production in 1950 – officially due to health reasons.

The last revival of semi-coke and coke production followed in the period between 1957 and 1967, when a broad range of experimental work was performed in cooperation with domestic and foreign institutes. Semi-industrial coke production (in Zabrz; Poland) was carried out, and modern Lurgi (Frankfurt, Germany) distillation equipment was purchased in the 1960s. Laboratory and semi-industrial experiments revealed that best results – i.e. 96 % of semi-coke (dry distillation at 500°C) and 90 % of coke (dry distillation at 950°C) – would be achieved by pre-drying lignite from about 45 % (raw state) to 15 % moisture content. Calorific values of dried lignite (ca. 15 % moisture), semi-coke, and coke varied around 17–18 MJ/kg, 24–25 MJ/kg and 26.5 MJ/kg, respectively (SEHER, 1995, p.367). An experimental use of the Velenje coke in the Jesenice (Slovenia) Ironworks also gave promising results. But, again, true production never started. Stopping of the project was officially explained by too high total investment costs for the complete technological equipment. Pre-drying of lignite, tested e.g. in Köflach, Donawitz (Austria) and in Belgrade, was also evaluated as much too expensive.

The most attractive plan to transform lignite into a higher grade product was undoubtedly that of lignite gasification. First studies, mostly carried out at the Chemical Institute in Ljubljana, commenced in 1948. A real lignite gasification programme started in 1961. It was planned that  $500 \times 10^6 \text{ Nm}^3$  of clean gas with a calorific value of 17.5 MJ/Nm<sup>3</sup> would be produced annually from 1 Mt of dry lignite (i.e. from 1.4–1.5 Mt of raw lignite). Different chemicals would be produced in economic quantities parallel with the gasification of lignite. A great advantage of the process, already pointed out at that time, would be the cleaning of the synthesis gas, i.e. a considerable removal of hydrogen sulphide, carbon, nitrogen and sulphur oxides, mercury, and particulate matter from gas. A great part of the Slovenian gas consuming industry supported the gasification programme, and a pipeline system of a starting length of 255 km was planned. But during five years of planning, from 1961 to 1965, the investment price of the project increased by more than three times. Lignite production should increase from 3.0 to more than 6.5 Mt/a. To cover the increased demand, the Šoštanj field and a surface mining field in the E, in close vicinity of Velenje, should be opened. Obviously this would have a dramatic influence on the entire environment. Further on, the final price of the gas from lignite was not found to be competitive with the prices of imported natural gas at the time. Due to all these reasons, governmental economists decided to stop the lignite gasification programme in 1965.

Even today, the technological and environmental aspects of lignite gasification seem interesting. The gasification of coal, either underground or in the so called IGCC plants, is becoming (again) a more and more promising clean-coal technology to ensure a stable energy mix, environmental protection and strategic security. This is especially important in a world with several extremely rapidly developing and highly energy consuming economies, with political conflicts causing instability in energy supply, and in a time of great environmental concerns (e.g. global climate change).

The period from 1950 to 1965 was significant for coal science, because profound fundamental and applied scientific work was introduced into multidisciplinary studies of coals world-wide. In Slovenia, coal science gained a lot from geological, petrological, chemical and

technological studies carried out by outstanding coal geologists and mining engineers including Milan HAMRLA, Zora GERMOVŠEK and Avgust ČEBULJ, and chemists such as Maksimilijan SAMEC, Dušan HADŽI, Boris LAVRENČIČ, Franc JENČIČ and co-workers. It is beyond the scope of this thesis to comment in detail all their achievements, but some of the greatest and most influencing studies should be cited here anyway (including also the period after 1965 and mentioning some additional authors): HAMRLA (1959, 1985/86, 1987, 1989) studied the rank of Slovenian coals, performed ground-breaking studies on coals in the karst region, and contributed significantly to the characterization of the maceral bituminite (in STACH et al., 1982, p.259); GERMOVŠEK (1963) published a study entitled “Problems of petrographic classification and nomenclature of brown coals in Slovenia”; ČEBULJ & GERMOVŠEK (1965) investigated the relation between coal facies and briquetting properties; KUŠČER (1967) published a fundamental geological study of the coal-bearing Tertiary formation in the Zasavje region; DROVENIK (1984) authored a textbook on coal, oil and gas and their deposits in separate chronostratigraphic units throughout Yugoslavia (and the world); and PIRC & ŽUŽA (1989) studied trace element contents in selected Slovenian coals.

In the early 1950s, a specialized chemical laboratory for coal analysis was set up at the Trbovlje Coal Mine, which was for many years led by Teodor ŽUŽA and Zora KALAN. At present, two additional laboratories for coal analysis operate at thermal power plants in Velenje and Ljubljana.

### **1.5. General problems encountered with the Velenje lignite mining**

Probably the most outstanding feature of coal mining in the Velenje basin is underground mining within a very thick lignite seam. Therefore, a great majority of mine workings is located within the lignite seam. Its thickness and the relatively small lateral dimensions are an advantage with regard to the concentration of huge reserves, but also cause problems. In order to excavate lignite as efficiently as possible by modern underground long-wall exploitation, a specific, highly mechanized “Velenje mining method” has been introduced, which is characterized by an intensive vertical concentration of excavated lignite. But in spite of such mining, excavation losses still amount to around 33 % (VEBER, 1999). Another disadvantage is a wide geomorphological impact on the surface due to subsidence above the mine. In addition, the transport and filling of voluminous excavated underground mine workings by ash to diminish subsidence of overlying strata and to stabilize active mine workings are costly. Also costly is the building of mining roads because they must be all supported by iron arcs and protected by wood. Stable (e.g. main transportation) roads must also be cemented to prevent coal fires. Water bearing sands above the lignite seam and Triassic dolomite in the basement need to be continuously dewatered. The amount of water which must be pumped to the surface exceeds the lignite production. For example, in 1998, dewatering amounted to 3.76 Mm<sup>3</sup> of water, and lignite production to less than 4.1 Mt or less than 3.2 Mm<sup>3</sup> (at vol. mass 1.28 t/m<sup>3</sup>) (data from VEBER, 1999, p.15, 29, 38).

Another spectrum of problems refers mainly to mine safety. Different dangers were diversely problematic in different periods and mining sites. They depended on technologies and equipments, safety measures, and bulk geomechanical parameters connected with the stress field and its changes. Well known risks occurring during the Velenje underground lignite mining comprise:

- danger of coal gas explosions,
- possibility of spontaneous combustion and consequently of underground coal fires,
- risk of water intrushes from different aquifers,
- danger of rock-falls of larger lignite masses (also with gas exhalations)
- instantaneous gas and lignite outbursts,
- pillar shocks and lignite out-gushes.

Explosions of coal gases, which might accumulate due to bad ventilation, have not occurred in Velenje for a long time, but disastrous accidents are known from the history, especially the two catastrophes in 1893 when 31 miners died. It was the time when opening shafts were still in construction and efficient aeration had not been achieved yet.

Almost 30 tragic events happened due to rock-falls of lignite masses in the past, especially at exploitation places where lignite was not supported tightly and early enough. In two cases, gas exhalations causing also human casualties occurred simultaneously with lignite rock-fall.

Coal fires and water intrushes did not cause human casualties but huge material damage.

Underground fires, the widest in 1903, were caused due to insufficient sealing of open lignite surfaces.

The first huge water intrush happened in 1918 with a starting water amount of 9 m<sup>3</sup>/min. Several water intrushes happened in 1973, with starting water amounts ranging from 2 to 15 m<sup>3</sup>/min. The source of all intrushes was the Triassic dolomite along the northern margin of the Velenje basin, where the lignite seam closely overlies the water-bearing dolomite.

Instantaneous coal and gas outbursts started to occur with increasing depth of the mine (down to the level of -62 m, i.e. 350–450 m below the surface) after 1958. In the next twenty years, 11 miners were killed in four out of seven accidents. Gas and coal outbursts are characteristic mostly for the Preloge field, which is the southern and western part of the mining area. At present, coal is exploited in depths below level -100 m. The next fatal event after 1977 happened in February 2003. This was a gas outburst in the exit mining road on the level of -90 m in the Preloge field (**Fig. 6.41**). Two miners died on the location. All such events are documented in detail at the Velenje Lignite Mine and at the Energy and Mining Inspectorate of the Republic of Slovenia. A modern monitoring system of gas contents, types of gases and their temporal behaviour is established at the mine. If high amounts of gases are detected in separate mine localities, the working crews are immediately moved out of the way. However, all tragic events happened very instantaneously, and could not be predicted with certainty. Known signs, which potentially predict a danger of gas outbursts, mostly derive from experiences of the miners. Among them the following are identified most often: increased frequency of pillar shocks, increased frequency of lignite claps, inflows of bubbling water, gushes of lignite, etc. In almost all cases, outburst events were connected with transitions from – in mining jargon – “hard” to “soft” lignite, and with fault zones. However, in a great majority of critical circumstances and warning signs, nothing happened. Gas outbursts mostly occurred in the uppermost part of the lignite seam, under the impermeable roof strata (“hanging wall” in the mining jargon), in parts of the mine with no previous workings. It was registered as well that the continuation of work after a period of nonworking represents an increased danger. Instantaneous coal outburst amounts ranged between 30 and 130 tons and volumes of gases between 2000 and 3000 m<sup>3</sup>.



At the beginning of gas and coal outburst occurrences it was supposed that drilling prior to road advancement would give positive results concerning the degasification of coal ahead the lignite face or lignite longwall, but this did not give good results. Most probably because of this reason, it was, up to the present, never seriously planned to exploit coal gases in the sense of coal-bed methane (CBM) technologies in Velenje.

Pillar shocks also started to occur more frequently and dangerously when mine workings deepened. In the central part of the Preloge field, according to the documentation of the mine, they are concentrated in an about 50 m wide N–S trending belt. This geometry coincides with the N-S fault system (**Fig. 6.35**) running obliquely to the WNW–WSE trending strike-slip Šoštanj fault.

It is well known that hazardous phenomena as described above occur in many coal-exploitation environments. They are specific for different environments, specificities being to a high degree the consequence of geological particularities. These should be explored as well as possible and most thoroughly understood. Exploration and research, applied and fundamental aspects meet interactively in the study of the coal-bearing environments and coal exploitation. The achievement of optimal economic efficiency and at the same time optimal mine safety, are undoubtedly the key managing objective of every modern coal mining company.

For the above reasons, multidisciplinary mining-geological exploration of the deposit has always been a main task of the Velenje Lignite Mine's management and professional staff, often in cooperation with external institutions and experts. Owing to technologically modern mining processes and monitoring, strict safety precautions, and both fundamental and applied study work, the Velenje Lignite Mine undoubtedly belongs to highly safe collieries in comparison to similar mines in the world.

## **1.6. Basic geological and geotechnical studies of the Velenje lignite deposit in the last 40 years**

Mining areas very often represent geologically best explored terrains of individual countries and geological formations, respectively. Occurrence and prospecting of ore bodies, study of their quality and reserves, study of mining conditions and the need to solve different problems of mining related to different geological phenomena are in fact the reason why mining areas are so well investigated. This holds true also for the Velenje lignite-bearing basin. In order not to go too far into the history, only basic geological and related geotechnical studies from the last 40 years or so will be briefly described in the following.

### **1.6.1. Geology of the Velenje basin**

Present understanding of the regional geological setting of the Velenje basin and its surroundings results to the greatest part from a decade of field mapping carried out by the Geological Survey Ljubljana during the 1960s and the 1970s. The results are published as the Guidebook of the Slovenj Gradec sheet – Basic Geological Map of SFR Yugoslavia in the scale of 1:100,000 (MIOČ & ŽNIDARČIČ, 1978). The basis for this map was field mapping in the scale of 1:25,000 and the geological map of this scale is still today the most detailed one for the Velenje basin. Almost all other mining areas in Slovenia were mapped in the scale of

1:5,000 or at least of 1:10,000. The reason, why more detailed geological mapping was not performed in the Velenje basin is most probably that – because of the simple geometry of the Velenje lignite seam – prospecting of the lignite seam in the Velenje basin was never a major problem. This is clearly different to most other coal and ore deposits, which are often severely tectonically deformed.

Systematic exploration of the lignite deposit using multidisciplinary techniques was performed during the 1960s and 1970s, and was intensified during the 1980s. A complex geological understanding of the whole basin and the lignite seam, comprising lithology, stratigraphy, geometry, tectonics, grade and reserves of lignite, rock-mechanical and hydrological properties of lignite and basin sediments, was gained from numerous borehole-logging data, in-well geophysical measurements, petrologically and chemically analyzed samples, hydrogeological tests etc. Up to the present, but mostly already up to the end of the 1980s, more than 600 boreholes in a total length exceeding 200 km were drilled from the land-surface downwards through the lignite seam (see also Facts about the lignite seam – **Tab. 2.2**). The three deepest boreholes, 9/43, P-12o/92, and J-1g/05, attained depths of 869 m, 1603 m, and 2146 m. They were mainly planned to reach the pre-Tertiary basement in the centre of the basin, but, quite surprisingly, especially concerning the deepest one, did not reach this goal.

The leading geologist engaged with fundamental geology of the Velenje basin in the 1970s and the 1980s was Aleksander BREZIGAR. In the mid-1980s, he published alone and with co-authors several key papers on the lignite seam (BREZIGAR, 1985/86), the paleontology of the Plio-Pleistocene sediments (BREZIGAR et al., 1985/86), the geological setting of the pre-Pliocene basement (BREZIGAR et al., 1987), and nonmetallic mineral materials of potential economic value (ŠTERN et al., 1987). In his papers, he also gave an overview of older studies, therefore, these will not be dealt with here more in detail. To a great part, the cited papers resulted from his outstanding *chef d'oeuvre* known as the “Sedimentary model of the Plio-Quaternary deposits of the Velenje basin”, archived as a study work at the Geological Survey in Ljubljana (BREZIGAR, 1981, in Slovene). In this work, his introductory sentence saying that “the Pliocene sedimentary fill of the Velenje basin represents a complex cycle from terrestrial, over marshy to lacustrine sedimentary environment, and back, from lacustrine over marshy to terrestrial environment” is one of the fundamental theses concerning general understanding of the sedimentary environments and processes taking place in the Velenje basin evolution. On the basis of sedimentary and palaeontological characteristics studied in boreholes and through a net of geological profiles, he differentiated the strata lying under the lignite seam into units I, II and III, and the strata overlying the lignite seam into nine units from A to I. He termed the lignite seam as the unit 0 (zero). Further on, in the overlying strata, he recognised an alluvial fan deposition in the central northern part of the basin.

New ideas on the Neogene evolution of the Pannonian Basin System and adjacent areas were stimulated by the AAPG Memoir 45 entitled “The Pannonian Basin – A Study in Basin Evolution” (edited by ROYDEN & HORVÁTH, 1988), as well as by papers of RATSCHBACHER et al. (1989; 1991), which introduced the concept of lateral extrusion of the Eastern Alps. They showed that large parts of the Eastern Alps moved eastward during Miocene times as a result of the ongoing convergence of the Adriatic and European tectonic plates. These ideas strongly influenced research on the Velenje basin as well.

In the 1990s and 2000s, several multidisciplinary studies focused to stratigraphy, paleogeography and regional tectonic deformations (FODOR et al., 1998, 2002; JELEN et al.,

1998; TOMLJENOVIC & CSONTOS, 2001), geothermal gradients (RAVNIK et al., 1995), maturation of organic matter (RAINER et al., 2002, 2009), hydrocarbon source rocks and generation (BARIĆ et al., 1996; HASENHÜTTL et al., 2001), and subsidence and thermal histories of sedimentary basins in the junction zone of the Alps, the Dinarides and the Pannonian basin (EBNER & SACHSENHOFER, 1995; SACHSENHOFER et al., 1998, 2001). Many of these studies included the Velenje area and were carried out in fruitful cooperation between Austrian, Croatian, German, Hungarian and Slovenian geologists.

From 1995 onwards, Marko VRABEC from the Department of Geology (NTF - University of Ljubljana) studied the tectonic evolution of the Velenje area in different scales. He started with structural analysis of the southern part of the Preloge pit of the Velenje Lignite Mine (VRABEC, 1995), and continued by studying the style of postsedimentary (post-lignite deposition) deformations in the Velenje basin (VRABEC, 1999), kinematics of the Šoštanj fault (VRABEC et al., 1999), and regional tectogenesis (VRABEC & FODOR, 2006). Furthermore, since 1998, he permanently studies in great detail tectonic elements of the lignite seam by underground mapping of the lignite exposed in advancing long-walls. He also introduced 3-D modelling techniques into structural models of sedimentary basins as well as into applied models of different lithological, rock-mechanical, petrographical and other data.

### **1.6.2. Hydrogeology**

Besides fundamental geology, hydrogeology and geomechanics were the primary study objects in the Velenje basin in the last 40 years.

Hydrogeological studies and tests, particularly oriented to dewatering of hangingwall and inter-lignite sands, and to control water inflows and intrushes from the pre-Tertiary carbonate rocks as already cited in the previous chapter, were led in the 1960s and early 1970s by Marijan MARIN and later on for many years by Miran VESELIČ and his group at the Geological Survey in Ljubljana (GeoSS). As a result of their excellent work, almost all hydrogeological problems are now solved and managed more or less routinely by the hydrogeological service at the mine. Questions related to the chemistry and origin of waters from different aquifers were studied using hydrogeochemical methods (MALI & VESELIČ, 1989) and by isotopic methods (URBANC et al., 2000).

### **1.6.3. Geomechanics and studies related to coal and gas outbursts**

A similar conclusion as for hydrogeology is true for geomechanics. Mining and engineering geology experts from academia, institutes and the VLM solved many questions dealing with geomechanical characterization of the basin strata, analyses of stress fields, mining-induced subsidence, natural and induced seismicity within the mining area and beyond, prediction of rock-mechanical circumstances within the lignite seam on the basis of the variability of the lignite quality, processes of lignite pulling-down during exploitation, and some other themes. At least the following names should be mentioned here in alphabetical order: Rudi AHČAN, Uroš BAJŽELJ, Andrej BLAŽIČ, Evgen DERVARIČ, Robert HOBLAJ Jože HRASTNIK, Slavko JANEŽIČ, Franc KOČAR, Marko KOČEVAR, Robert LAH, Jakob LIKAR, Janez MAYER, Milan MEDVED, Zdenka ŽORŽ POPOVIČ, Franc PUC, Mihael RIBIČIČ, Marjan TAMŠE, Boris SALOBIR, Simon ZAVŠEK Franc ŽERDIN, and Franc ŽIGMAN.

In the early 1980s, a computerized data base of geomechanical data for the Velenje basin was created by RIBIČIČ (1982). Two years later, a very extensive study entitled “Geomechanical model of the intact Velenje basin strata” was done by ŽORŽ-POPOVIČ et al. (1984), whereas geomechanical characteristics of sediments/sedimentary rocks already affected by mining-induced processes were finally interpreted in a study of BREZIGAR et al. (1987). Both studies give an overview of statistically representative values of rock-mechanical parameters separately for “BREZIGAR's” (1981) sedimentary units I–III, 0, and A–I, as well as for five different parts of the mining area. Both studies are still greatly valid today. An interesting elaboration, a classification of the lignite deposit on the basis of correlation between rock-mechanical characteristics and calorific value of lignite was done by KOČAR et al. (1988). Studies such as those of RIBIČIČ (1987) and KOČEVAR et al. (1989) about implementation of in-situ measurements in thick coal seams considerably influenced systematic in-situ measurements of geomechanical parameters within the mine workings, especially of lignite itself, which expanded during the first half of the 1990s by a team of colleagues: Jakob LIKAR (Institute of mining, geotechnology and environment; IMGE), Marko KOČEVAR (GeoSS) and Simon ZAVŠEK (VLM). These studies were essential as they initiated a “re-start” of applied petrographical investigations of lignite. This was, when the colleagues dealing with geomechanics wanted to understand the relation between rock-mechanical parameters and the composition, texture and structure of lignite.

In addition to geomechanical studies<sup>10</sup>, studies of sudden outbursts of coal and gases into the mine workings were also a great field of research mainly led by the experts for geomechanics. This theme is very topical still today and as it is rather complex, also researchers from other disciplines, including structural geologists, chemists, coal petrologists, isotope geochemists have been invited to cooperation.

Specific situations of coal and gas outbursts are documented in detail at the VLM. An overview of these events, related studies from the 1960s onwards and analysis of mechanisms which are critical for lignite masses to be burst out have been summarized and thoroughly interpreted in the dissertation of LIKAR (1995). In the final summary and recommendations he mentions that “varying petrographic structural characteristics of lignite layers have not been discussed in detail, since detailed analyses are presently in the initial phase”.

Indeed, in the following years, a wide range of petrographical investigations on complementary macro-, meso-, and micro-scale levels have been carried out in the frame of annual projects between the VLM and the GeoSS. In the first half of the 2000s, a fruitful cooperation between experts from the Institute of Strength Physics and Material Science from Tomsk (Russia), from the Department of Geology at the University of Ljubljana and from the VLM was established. PSAKHIE et al. (2000, 2001), and ZAVŠEK (2004) made a great step forward in modelling petrographically discriminable varieties of lignite under different external stresses and the presence of gases responsible for the development of cracks and hence failure (or even explosion) of the material. As a novelty in geology and mining, they applied the method of “movable cellular automata” (MCA) for “as received” samples and a method of “symbiotic cellular automata” (SCA) for samples under the presence of gases. In this context, the automata are defined as source elements which encompass structural-petrographic elements such as contents of different lithotype components, their size, shape,

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<sup>10</sup> The authors are aware, that the commentary of geomechanical studies (as well as of hydrogeological studies in **Chap. 1.6.2**) is very scarce and incomplete. More than 200 reports about Velenje are archived at the GeoSS only, but little has been published in literature.

orientation, and packing, together with their specific geomechanical properties, as well as consideration of the accompanying structural features as faults, cracks, and bedding elements.

In 1997, Stanko HOČEVAR from the National Institute for Chemistry in Ljubljana and his student at the time Alenka ZAPUŠEK started to study adsorption and desorption of gases at low pressures and normal temperatures (using so called Dubinin-Radushkevich, Horwath-Kawazoe and BET equations) on samples of different lithotypes of lignite. As a result, their laboratory experiments showed significantly different adsorption and desorption properties of different lithotypes, mainly as a function of differences in porosity parameters (ZAPUŠEK & HOČEVAR, 1998; ZAPUŠEK et al., 1999). For example, the specific surface of pores of homogenous fine-detrital lignite amounts to more than 180 m<sup>2</sup>/g, whereas that of xylite is “only” 35 m<sup>2</sup>/g. For coals in general, LIKAR (1995, p.10 – after different authors) cites the range from 40 to 80 m<sup>2</sup>/g. In lignites, CO<sub>2</sub> is often considered as more dangerous and insidious than CH<sub>4</sub>, because it is heavier, less mobile, and has a smaller molecular size. Under pressure, it is almost entirely (up to 90 %) adsorbed on the pore surfaces (e.g. LIKAR, 1995; PEZDIČ et al., 1999 – both after LITWINISZYN, 1990). The CO<sub>2</sub>/CH<sub>4</sub> ratio in coals (by volume per mass unit of coal) is widely reported to be about 2, however, in lignites it can be as high as 10 (e.g. MASTALERZ et al., 2004). CO<sub>2</sub> in coal under pressure is immobile until the porous structure of coal is not disturbed by external forces. In Velenje, at “normal situations”, amounts of from-lignite-released gases depend on petro-chemical characteristics of coal and of technology of advancement and of lignite excavation. As cited in LIKAR (1995; p.34–42), gas contents per mass unit range from 10 to 26 m<sup>3</sup>/t, and per time unit from 1 (drilling) to 4 (exploitation with longwall-face cutting) and even to 8 m<sup>3</sup>/min (at experimental/controlled release of stresses within the lignite mass around a mine working). CO<sub>2</sub>/CH<sub>4</sub> ratios (by volume per mass unit of coal) generally vary between 2 and 3. However, on the basis of mass spectrometric measurements, KANDUČ et al. (2003) (see the study cited in the paragraph below) report that the CO<sub>2</sub> : CH<sub>4</sub> ratios can vary from 30 : 70 vol.% to 100 : 0 vol.%. As known from laboratory adsorption-desorption tests, one disadvantage of CO<sub>2</sub> is also its incomplete desorption from coal, especially if the coal is homogeneously fine-detrital. This is most probably also one of the reasons, why attempts of lignite degasification, e.g. by drilling, were not successful in Velenje (up to now).

At the end of the 1990s, a research project entitled “Origin, transport, and accumulation of gases in the Velenje lignite” started to be carried out by Jože PEZDIČ (NTF – University of Ljubljana), and his research group from different institutions (Institute Jožef Stefan – IJS, GeoSS, VLM). Laboratory simulation of gas adsorption – gas desorption processes on different lithotypes under high pressures (up to 100 bars) (PEZDIČ et al., 1999), study of dynamical alternation of gas composition (CO<sub>2</sub> versus CH<sub>4</sub>) due to advancement of the lignite working face (KANDUČ et al., 2003), and analysis of carbon isotopic composition of CO<sub>2</sub> and CH<sub>4</sub> to ascertain their origin (PEZDIČ et al., 1998, KANDUČ et al., 2003, KANDUČ & PEZDIČ, 2005) were the main topics of the mentioned project.

In the study of PEZDIČ et al. (1998) not only isotopic composition of gases but also – for the first time! – carbon isotopic composition of different lignite lithotypes was investigated. Few years later, a systematic carbon isotopic characterization of lignite (incl. wood and extracted cellulose) throughout the reference P-9k/92 core-profile was carried out by BECHTEL et al. (2003), dealing primarily with biomarker investigations. Also very systematic carbon and nitrogen! isotopic characterization of different lithotypes throughout the lignite seam was done by KANDUČ et al. (2005).

Many studies cited above revealed that knowledge about petrographic heterogeneity of lignite is crucial to understand the complexity of gas properties and gas behaviour in the course of lignite mining. Spatial study and prediction of more or less hazardous zones dependant to a considerable degree on compositional, textural and structural properties of lignite masses as well as on different tectonically caused effects still remain among the topical montan-geological research themes in the Velenje mine.

#### **1.6.4. Data management and elaboration of coal reserves**

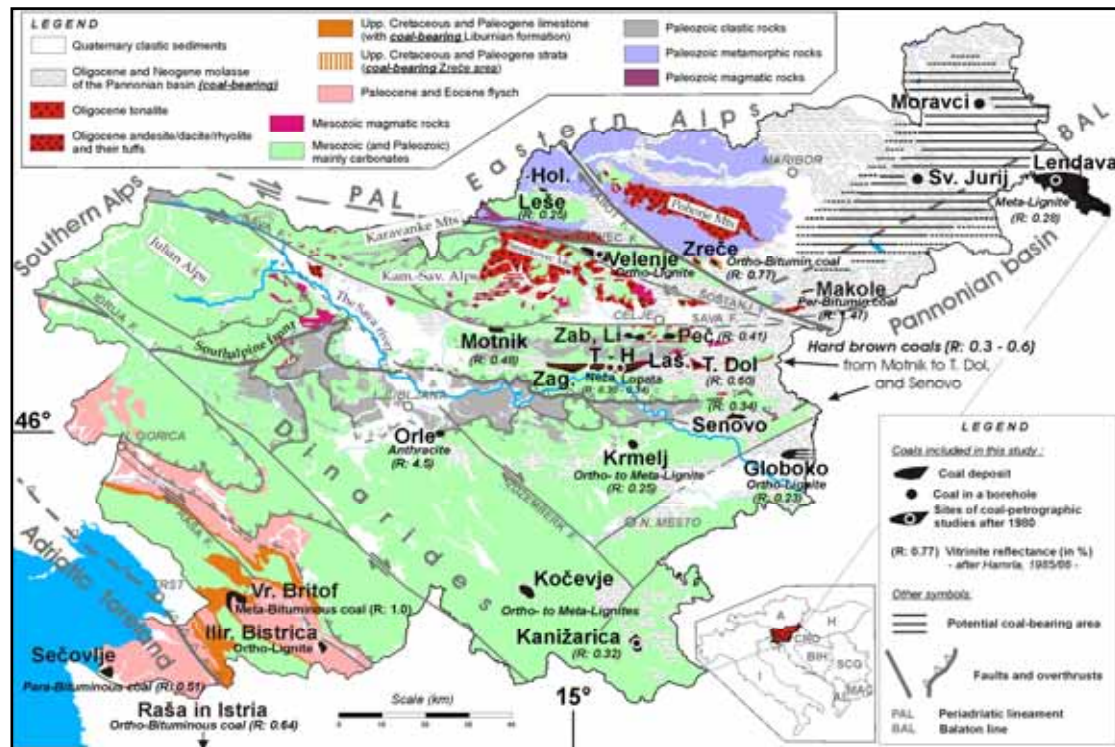
In order to present the complex geology of the deposit in the form of profiles, structural (isoline) maps, and, more recently, 3-D presentations, comprehensive databases of a number of geological and geotechnical parametres are necessary. The development of computer aided techniques started in the late 1970s. Ivan SUPOVEC, at the time with the VESELIČ group at the GeoSS, was one of the key persons who introduced computer methods into geology not only of the Velenje basin but in Slovenian geology in general.

Evaluation of the in-seam coal quality, evaluation of the in-seam lignite reserves, and planning of the mine workings are a permanent task of the mining engineers and geologists at the mine. The last elaboration on the lignite reserves was done in 1999 by Igor VEBER, the head geologist at the VLM from the beginning of the 1990s onwards.

## 2. GEOLOGICAL SETTING AND FACTS ABOUT THE VELENJE LIGNITE

### 2.1. Geological setting

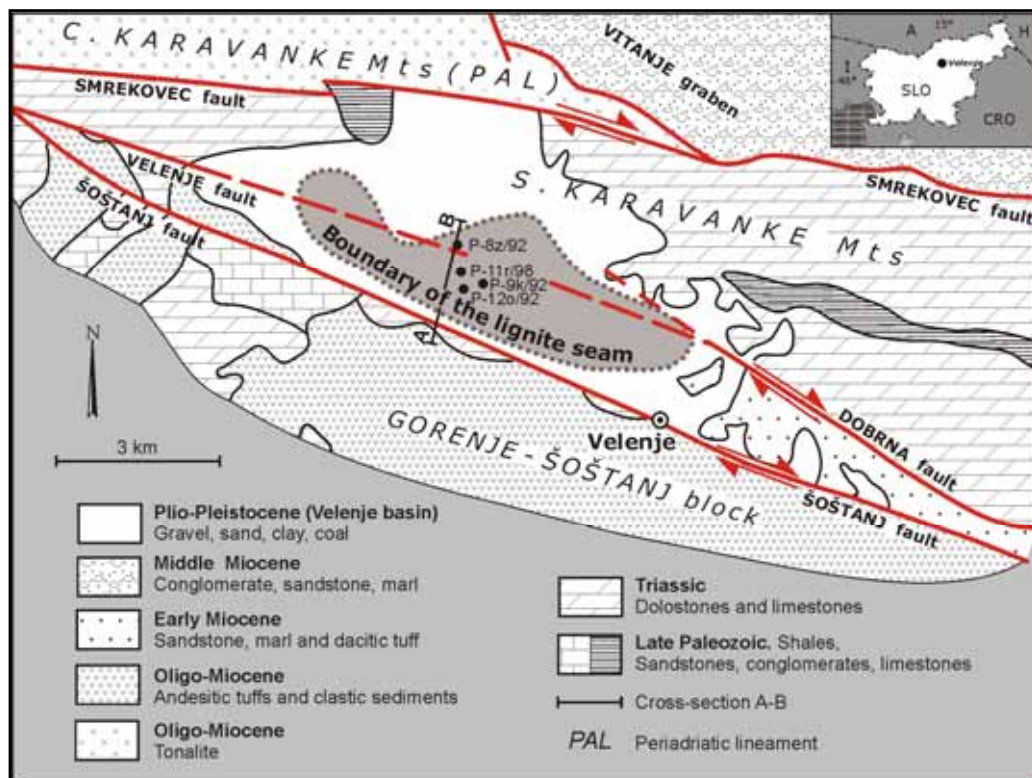
The regional geological setting of the Velenje area will be summarized here mainly according to the following authors: MIOČ (1978, 1983); BREZIGAR (1985/86); BREZIGAR et al. (1987, 1992); VRABEC (1999); VRABEC et al. (1999); and PREMURJ (2005). On the Basic Geological Map of Yugoslavia in the scale of 1:100,000, the geology of the Velenje basin and its surroundings is presented on the sheets Slovenj Gradec (MIOČ & ŽNIDARČIČ, 1976) and Ravne na Koroškem (MIOČ & ŽNIDARČIČ, 1981). The location of the Velenje basin on a simplified geological map of Slovenia is shown in **Fig. 2.1** together with some other important coal deposits.



**Fig. 2.1:** Simplified geological map of Slovenia with position of selected coal deposits (adopted from MARKIČ et al., 2007). The map is compiled from 23 sheets of the Basic Geological Map of Yugoslavia 1:100,000 (made by the Geological Surveys in Ljubljana and in Zagreb, and published mainly by the Federal Geological Survey in Belgrade between 1964 and 1998). Tectonics is summarized from PLACER (1998). Terms for rank of coals are given according to the ECE-CSE-UN (1998) classification. Mean random vitrinite reflectance (R) values are taken from HAMRLA (1985/86). In NE Slovenia, thin coal layers are known from numerous boreholes, but only two of them are shown in the map. Black areas showing the coal deposits are not representative in sense of dimensions of coal deposits and reserves, respectively – they are relatively large in cases of horizontally bedded deposits and relatively small in cases of coal deposits characterized by steeply inclined strata. Where not whole names for the shown coal deposits are written, the following abbreviations are used: Hol. – Holmec; Zab. – Zabukovica; Li. – Liboje; Peč. – Pečovnik; Zag. – Zagorje, T.-H. – Trbovlje–Hrastnik; Laš. – Laško; T. Dol – Trobni Dol; Vr. Britof – Vremški Britof; Ilir. Bistrica – Ilirska Bistrica.



According to the authors cited above, the Velenje basin is an intermountain lacustrine basin of the Pliocene to Pleistocene age, formed by polyphase dextral strike-slip faulting at the junction of the following three tectonic units: the Central Karavanke Mountains, the Southern Karavanke Mountains and the Gorenje-Šoštanj block (**Fig. 2.2**). The Central Karavanke Mountains are built from Permo-Triassic Variscan granite in the north, gneiss in the middle (out of Fig. 2.2) and of Tertiary (Oligo-Miocene) (Alpidic) tonalite in the south. The whole belt of the Central Karavanke Mountains, which is less than 3 km wide, represents the Periadriatic Lineament (PAL) tectonic zone. The Southern Karavanke Mountains are broadly characterized by Triassic limestones and dolostones, with a zone of overthrust Paleozoic shales, sandstones and conglomerates. The Gorenje-Šoštanj block, regionally belonging to the the Savinja Alps, is composed of Oligo-Miocene marls and sandstones intercalated by andesitic tuffs, as well as of late Paleozoic and Triassic carbonates. The Central and the Southern Karavanke Mountains are separated by the E–W trending dextral Smrekovec fault, which represents the southern boundary of the Periadriatic Lineament (PAL). The Southern Karavanke Mountains and the Gorenje-Šoštanj block are separated by the WNW–ESE trending dextral Šoštanj fault, which is a branch fault of the Smrekovec fault.



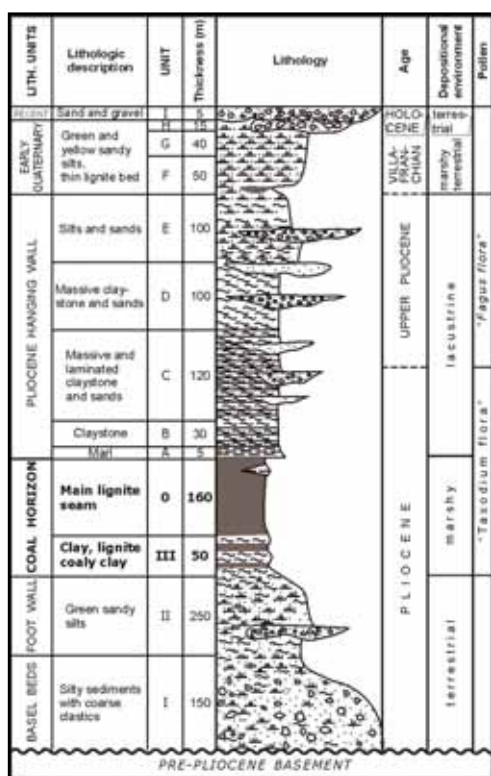
**Fig. 2.2:** Geological map of the Velenje basin and its hinterland (simplified after BREZIGAR, 1985/86; and BREZIGAR et al., 1987). Note the position of the A–B cross-section and of the P-9k/92, P-8z/92, P-12o/92 and P-11r/98 boreholes. The deviation of the lignite seam contour from the more ideal elliptical course in the north is interpreted as a consequence of clastic inflow into the peatland from the north (see more explanation in Chap. 6.4.1).

It is widely accepted that the Periadriatic Lineament (PAL) (**Fig. 2.1**) represents the contact zone between the Eastern and Southern Alps (e.g.: FANINGER, 1976; MIOČ 1978; PLACER, 1998; PREMUR, 2005; POLJAK, 2007; and older literature cited therein from KOBER (1915) and KOSSMAT (1924) onwards). In the lateral extrusion model of the Eastern Alps, the PAL is interpreted as the southern margin of the eastwards moving block. At least 100 km of dextral

displacement is estimated to occur along the PAL zone (RATSCHBACHER et al., 1991). VRABEC & FODOR (2006) termed the W–E trending PAL as the Periadriatic fault zone (PAF). According to these authors, the PAF borders together with the southern Sava fault a large dextral shear zone, which they termed as the Sava – PAF shear zone. The Velenje basin is situated in the northern part of the Sava – PAF shear zone. The dextral Labot (Lavanttal) fault, passing along the SW margin of the Pohorje Mountains, is still younger than the Smrekovec fault and displaces the Sava – PAF shear zone.

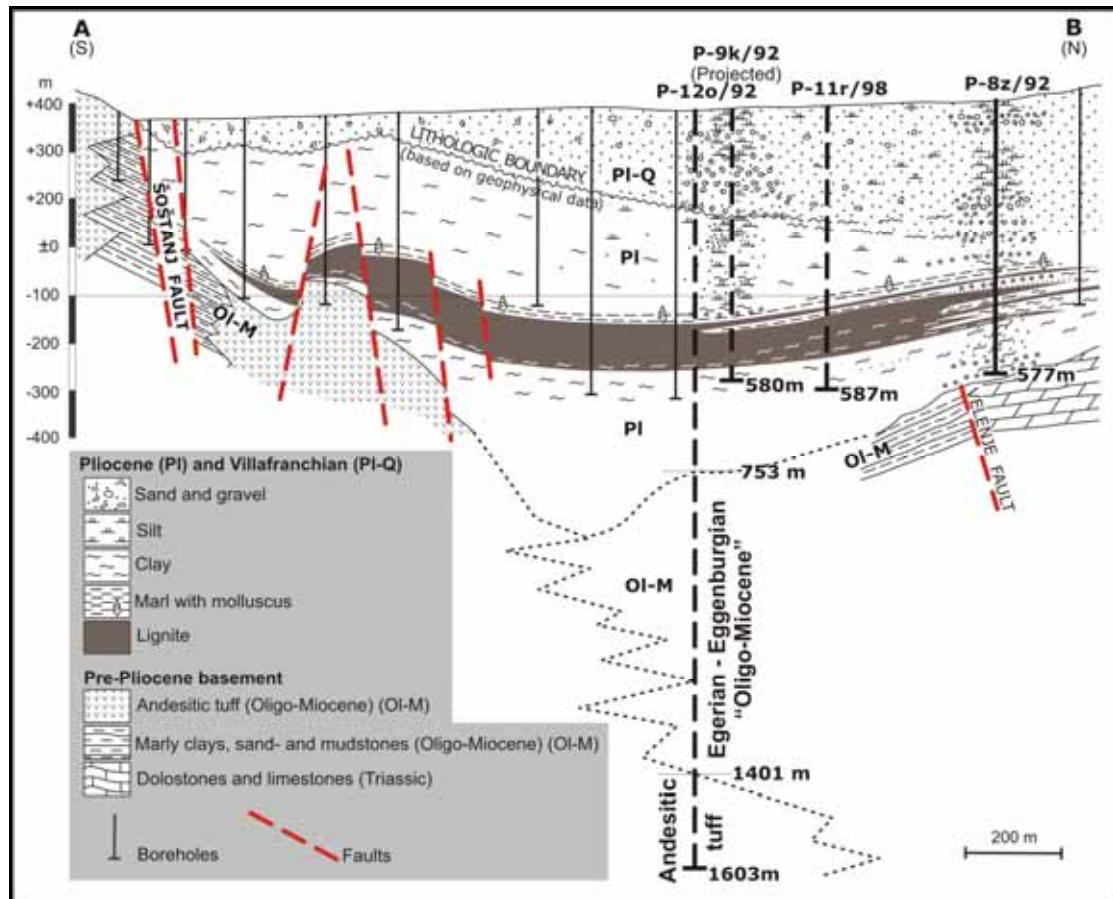
Dextral strike-slip faulting is typical for a large part of Slovenia (**Fig. 2.1**). HINTERLECHNER-RAVNIK & PLENIČAR (1967) were amongst the first to recognize this sense of displacement, when they studied the Smrekovec andesite and its tuff. On the basis of geological positions of the andesite bodies throughout northern Slovenia, they presumed dextral movements of an order of up to 25 km along the Sava fault and at least 25 km along the Smrekovec fault. Further on, they pointed out that also other “long and young faults of the NW–SE direction” in the Dinarides belong to strike-slip faults. Actually, besides the PAL (or PAF zone) and the Sava and Labot faults, also the young NW–SE trending (“Dinaridic”) faults (e.g. Žužemberk, Idrija, and Raša<sup>11</sup> fault) are of this type.

The Velenje basin is filled with Plio-Pleistocene sediments. It is about 10 km long and 4 km wide, bounded by the Smrekovec fault to the north and by the Šoštanj fault to the south (**Fig. 2.2**). In the central part of the basin, the Plio-Pleistocene clastic sedimentary fill is more than 1000 m thick (**Figs. 2.3 and 2.4**).



**Fig. 2.3:** Representative stratigraphic column of the Pliocene and post-Pliocene sedimentary fill of the Velenje basin (after BREZIGAR, 1985/86).

<sup>11</sup> Raša is a toponym with two meanings: 1) a small river and a valley in SW Slovenia after which the Raša fault is termed, and 2) hard coal deposit in Istria in Croatia, known for very sulphur-rich coal.



**Fig. 2.4:** Geological cross-section A–B (see Fig. 2.2) across the southern, lignite-bearing part of the Velenje basin adopted after BREZIGAR's (1985/86) profile 3–3'. Added are P-9k/92, P-8z/92, P-12o and P-11r/98 boreholes among which only the P-8z/92 is exactly on the profile. Basic geological facts along the P-12o/92 are summarized from VESELIĆ et al. (1993), an interpretation of the spatial contact between andesitic tuff and Egerian – Eggenburgian clastics is made by the authors.

The Pliocene sedimentary sequence is composed from bottom to top of terrestrial coarse-grained basal beds with a fining-upward trend, fine-grained marshy sediments with the main lignite seam, and of fresh-water lacustrine clayey, silty and sandy sediments with lenses of fluvial sandy gravels. At the top of the sedimentary fill, the Upper Pliocene sediments gradually transit into the Villafranchian sediments, which are marshy at the bottom – with a locally developed thin lignite bed – and terrestrial upwards. The youngest sediments in the region are sands and gravels of Holocene age (BREZIGAR et al., 1985/86). Petrological composition of the clastics is related to the petrology of the basement rocks and prevailing transport directions in different phases of the basin evolution.

A wide range of geological processes including strike-slip and reverse faulting, basin formation and inversion, magmatic activity, unroofing and erosion occurred in the transition zone between the Eastern Alps, Southern Alps, Dinarides and the Pannonian basin during Tertiary times (e.g. ROYDEN & HORVÁTH, 1988; RATSCHBACHER et al., 1991; TARI et al., 1993, 1999; EBNER & SACHSENHOFER, 1995; FODOR et al., 1998; KRALJ, 1996, 2000). These processes caused lateral and temporal heat flow variations. Vice versa, heat flow variations may affect the rheological properties of lithosphere (e.g. BUCK, 1991 and LANKREIJER, 1998) and, thus, geodynamical processes. The thermal history of Tertiary basins in the Alpine-Dinarides-Pannonian junction was studied recently by SACHSENHOFER et al. (2001) using

basin modelling techniques. This study suggests that heat flows were elevated in the Velenje area during Oligocene times, a result of Smrekovec volcanism. In contrast, heat flow was normal since at least late Miocene times and similar as today, i.e. between 50 and 60 mW/m<sup>2</sup> (RAVNIK, 1991; RAVNIK et al., 1995; RAJVER & RAVNIK, 2002). Organic matter of the basin sediments, including the lignite seam, was therefore subjected to normal geothermal gradients.

## 2.2. Facts about the Velenje lignite

The Velenje lignite seam is bowl shaped, approximately 8 km long, 2.2 km wide and on average 60 m, but locally up to 166 m thick (BREZIGAR, 1985/86, p.328) (**Figs. 2.2, 2.3 and 2.4**). Towards the margins of the basin, its thickness decreases, and the seam pinches out. Along the Šoštanj fault, it is tectonically displaced. Towards the north, it splits into several mineral-rich thin lignite seams. In the central area of the basin, it is embedded approximately in the middle of the clastic Plio-Pleistocene succession. To the south and to the north, it lies quite close to the pre-Pliocene basement.

The Velenje lignite is a humic type of lignite, more or less rich in xylite fragments, fusinite, and mineral matter. The later is composed of aluminosilicates but to a considerable degree also of carbonate minerals. The matrix of lignite is fine-detrital, dark brownish to dusky brown in colour. Petrographic heterogeneity is furthermore expressed by very different sizes, shapes, and orientations of xylitic fragments and by different degrees of gelification affecting more severely (and in an earlier stage of peatification) the fine-detrital matrix. Compositional and textural variations are expressed as bedding, from the laminar (<1 cm) to the thick bedding dimensions, but not exceeding approximately 2 m.

The lignite is dominated by huminite macerals. Liptinite and inertinite macerals are typically below 10 %. Grade of the “run-of-mine” lignite according to BREZIGAR (1985/86) is:

- calorific value: 7.5 to 12.6 MJ/kg,
- ash yield: 5 to 40 %
- moisture content: up to 45 %.

The ash yield decreases in general from the bottom toward the top of the seam. Hence, calorific value of raw coal increases upwards. Sulphur content of dry coal is reported to vary between 0.5 and 2.0 %. Average density as used for calculation of reserves is 1.28 g/cm<sup>3</sup>. Lignite quality as documented by VEBER (1999) and as recorded by the Republic Commission for the Mineral and Water Reserves Assessment (RCMWRA, 2002) is presented in **Tab. 2.1**. The Velenje field, where the exploitation of lignite is going on, comprises the eastern area of the lignite seam (**Fig. 2.2**). The Šoštanj field to the west has never been mined and the same decision has been made for the future. In **Tab. 2.1**, the coal rank by the huminite reflectance is cited after HAMRLA (1985/86), whereas by the gross calorific value (GCV) after MARKIČ et al. (2007).

The main facts about the lignite seam as summarized after VEBER (1999), VEBER & DERVARIČ (2004), VEBER & SUPOVEC (2006) are presented in **Tab. 2.2**.

**Tab. 2.1:** Coal rank and coal quality of the Velenje lignite. Abbreviations: GCV – Gross Calorific Value; Rr – huminite reflectance; M, A, OM – contents of moisture, ash and organic matter; NCV – Nett Calorific Value; S-tot. – total sulphur content; daf – dry, ash-free basis; ar – as received basis; d – dry basis. For data sources see the text.

Age	COAL  (whole deposit)	Coal rank			Coal quality							
		Class	GCV	Rr %	M	A	OM	NCV	S-tot	A	Grade	
		(by GCV)	MJ/kg		mass %			MJ/kg	mass %		mass %	
			daf basis		ar basis				ar basis	d basis	d basis	(by ash)
PLIOCENE	Velenje field	Ortho-lignite	24.57	0.24	35.70	15.80	48.50	10.45	1.38	2.15	24.57	low
	Šoštanj field		25.31		34.20	23.30	42.50	9.40	1.40	2.13	35.41	very low

**Tab. 2.2:** Facts about the Velenje lignite. It is evident that values of coal quality parameters (moisture, ash etc.) differ slightly from those in the text – the reason is the alteration of data sets through time due to proceeding mining and exploration.

### FACTS about the Velenje lignite

(Mainly after VEBER, 1999; VEBER & DERVARIČ, 2004; and VEBER & SUPOVEC, 2006)

- From 1873 onwards, **more than 600 boreholes** (structural, as piezometers, dewatering wells, wells for rock-mechanical measurements) with a total length of more than 200 km were drilled from the land-surface downwards through the lignite seam. In addition, 1500 underground in-lignite-seam boreholes with a total length of 90 km have been drilled until 1998 (VEBER, 1999), and even 2000 boreholes are mentioned by VEBER & DERVARIČ (2004).
- The deepest boreholes drilled from the surface: 9/43 – **869 m**; P-12o/92 – **1603 m**; J-1g/05 – **2146 m**
- Length of basic active mining roadways, mostly running within the lignite seam: **80 km**
- Mining method: underground longwall excavation, known as the “Velenje method”.
- Shape and dimensions of the lignite seam: – mega-lenticular (bowl-shaped, concave); 8,3 km long, 1.5–2.5 km wide, from a few metres at the periphery to more than 100-m thickness in the central part; elongated in WNW-ESE direction along the regional strike-slip Šoštanj fault
  - The greatest thickness: 168 m of “good-quality” lignite (VEBER, 1999), also reported as 164 m (MIOČ & ŽNIDARČIČ, 1978, p.58) and as **165.8 m** of “pure” lignite, respectively, in the 12f/74 borehole (BREZIGAR, 1985/86, p.328)
  - Average thickness of the lignite seam: **60 m**. Average depth of the seam: **300 m**
- Number of basic coal analyses: more than **1600**; the following average (avg.) values of coal quality parametres (as received basis – *arb*) refer to the present coal reserves:

PARAMETER	AVG. VALUE	PARAMETER	AVG. VALUE
Moisture	30 %	C-fix	20 %
Ash	22 %	Sulphur (S)	1.7 %
Vol. matt.	28 %	Calorific value	10.9 MJ/kg

- Lignite reserves in the Velenje field calculated on the basis of 35 systematic parallel profiles (at 75 m distances) and contour (seam-bottom and seam-surface) maps amount to **“at least 100 Mt”** (VEBER & DERVARIČ, 2004).
- The lowest acceptable calorific value taken into account at reserves calculations: 7.5 MJ/kg
- Today, the limit of the exploited lignite is at a calorific value above 8.4 MJ/kg
- Threshold from non-combustible into combustible rock / lignite: 4.2 MJ/kg
- Average calorific value of the above cited “100 Mt” lignite reserves: **10.9 MJ/kg**

### 3. PETROLOGICAL AND RELATED STUDIES OF THE VELENJE LIGNITE BEFORE 1992

#### 3.1. Petrography

When speaking about geology and petrology of coals in Slovenia, it is almost inevitable to mention the name of Milan HAMRLA. He was especially active in coal geology during the 1950s, in the first half of the 1960s, and during the second half of the 1980s. Three his reports about petrography of the Velenje lignite are archived at the GeoSS and the VLM, dating from 1952, 1955, and 1957.

In the first report, HAMRLA described basic macro-petrographic features of the Velenje lignite in terms of ratios between xylitic fragments of very variable dimensions and shapes and fine-detrital homogenous matrix (**Fig. 3.1**). He termed the latter, if amounting to more than 90 %, as “barski premog” (Slovenian translation for the German term “Moorkohle”). He mentioned that fusitic coal is rare and divided “barski premog” into two varieties: (1) the prevailing massive brownish coal, and (2) the densely cleated, darker, almost black one with even conchoidal fractures. The latter variety was termed “velenjit”. This term was used for years, although HAMRLA (1957) considered it only as a “provisional working name”. Indeed, following the ICCP<sup>12</sup> (1993) terminology (from TAYLOR et al., 1998, p.280, tab. 5.2), there is no need to use the term “velenjit”, because it is nothing else than a typical gelified variety of fine-detrital (matrix) lignite (**Tab. 6.1**). Similarly, the massive brownish variety of the “barski premog” is a typical fine-detrital (matrix) lignite with no (or weak) gelification. The next variety distinguished by HAMRLA (1952) was “metaxylite”, described as gelified xylite depleted in cellulose and occurring mostly in the lower part of the seam<sup>13</sup>. In his description of mineral matter (e.g. clay/marl partings and disseminations, pyrite/marcasite, and occurrences of some other small and hard-to-identify mineral/lithic grains), HAMRLA (1952) pointed out replacements of xylitic fragments by calcite (**Fig. 3.2**). The replacement often affects tree trunks in more or less vertical (growth) position. Based on this observation, HAMRLA interpreted them as a syngenetic result of calcitic sediment deposition on wood remnants exposed above the peat surface. The wood was the source of CO<sub>2</sub>, whereas marl was the source of Ca in the water percolating over the exposed wooden parts. Therefore, it can be inferred already from this description, that the Velenje lignite belongs to the so called Ca-rich type of coal. Based on observations made during a five-day survey in different parts of the

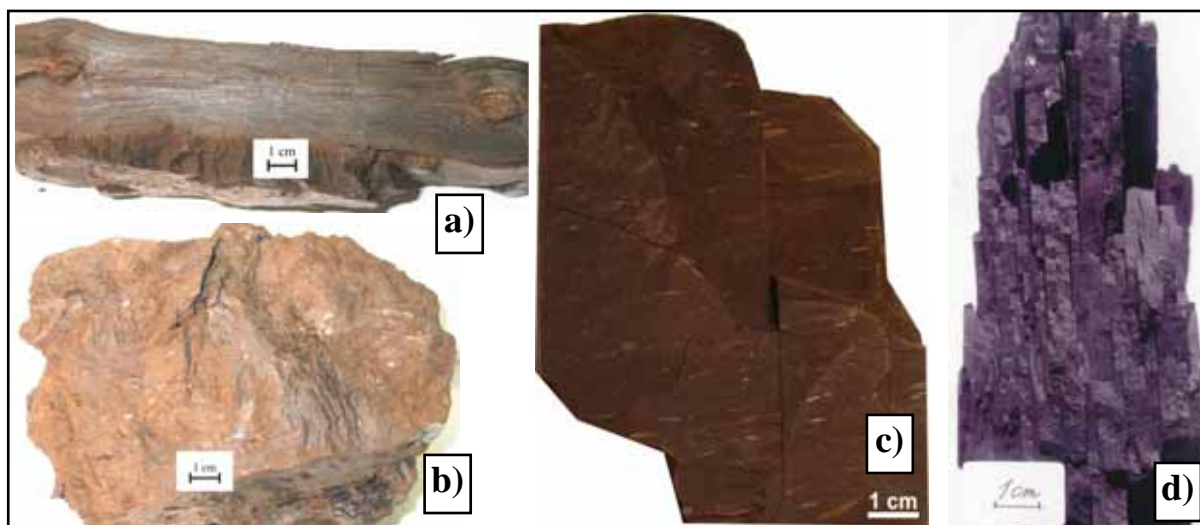
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<sup>12</sup> ICCP is the abbreviation for the International Committee for Coal Petrology, which was renamed into International Committee for Coal and Organic Petrology in 1995 (but retained the same ICCP abbreviation).

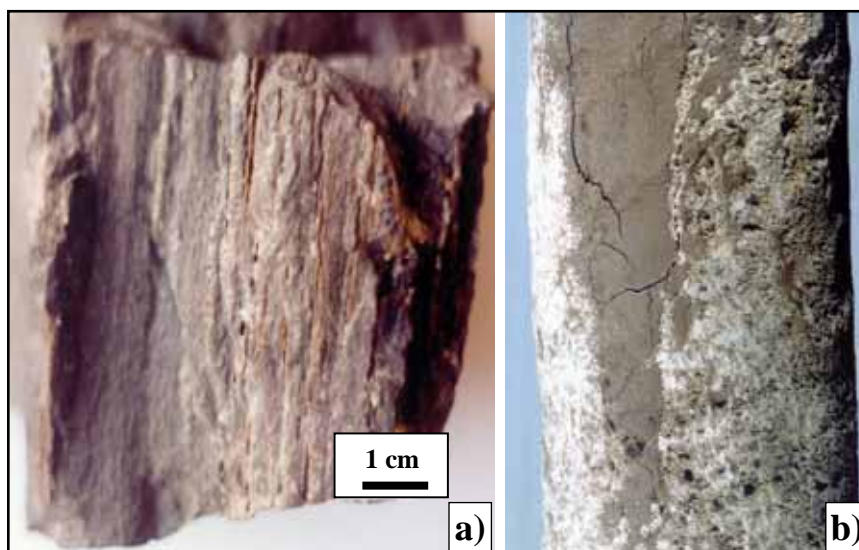
<sup>13</sup> The depletion in cellulose in “fossil wood” from the lower part of the seam was really confirmed by BECHTEL et al. (2003). However, the woods with low cellulose contents (10–15%) are formed by non-fluorescing textinite-B. This maceral variety is genetically related to degradofusinite, which results from (semi)oxidation. On the contrary, higher cellulose contents (25–35 %) are found in gelified woods, composed of (texto)ulminite-A, in the upper part of the seam. To the authors' experience, xylites from the lower part of the seam often exhibit very homogeneous, vitrain or bright coal-like appearance (“xylo-gelite”) and are hence considered as gelified. But this designation can be misleading and has to be always checked microscopically to distinguish between ungelified textinite-B and gelified (texto-)ulminite-A.



mine, HAMRLA concluded that xylite-rich coal is distributed along the periphery of the basin, whereas fine-detrital lignite (“barski premog”) prevails in the inner part of the basin. It is worth mentioning that this interpretation is still valid<sup>14</sup>.



**Fig. 3.1:** The most typical macro-petrographic varieties of the Velenje lignite: **a)** “Tabular” xylite – note two “outgrowths” on the left and right, and fine-detrital matrix coal at the bottom (where the scale is marked). **b)** Stocky (stout) xylite – note a slickenside at the bottom. **c)** Non-gelified brownish fine-detrital lignite with thin but clearly notable brown lenses of xylite that clearly exhibit the bedding planes. Vertical cracks are less frequent than in the right-most sample. **d)** Typical black homogeneous fine-detrital lignite, a gelified variety. “Velenjit” after Hamrla (1957). Very distinctive is a vertical system of cracks perpendicular to bedding.



**Fig. 3.2:** Calcification of xylite: **a)** Xylite, which was completely transformed to limestone. The limestone was later chemically corroded or “karstified”. Slightly visible is a vertical system of tracheids – see brown Fe mineralization (limonitization). **b)** Partial calcification (white) of xylite (dark) in borehole-core (ca. 6 cm in diameter).

<sup>14</sup> Today the sites of HAMRLA's observations are excavated, but in the 1990s and the 2000s, his interpretation was greatly confirmed by underground mapping (see **Chap. 6.3.3**).



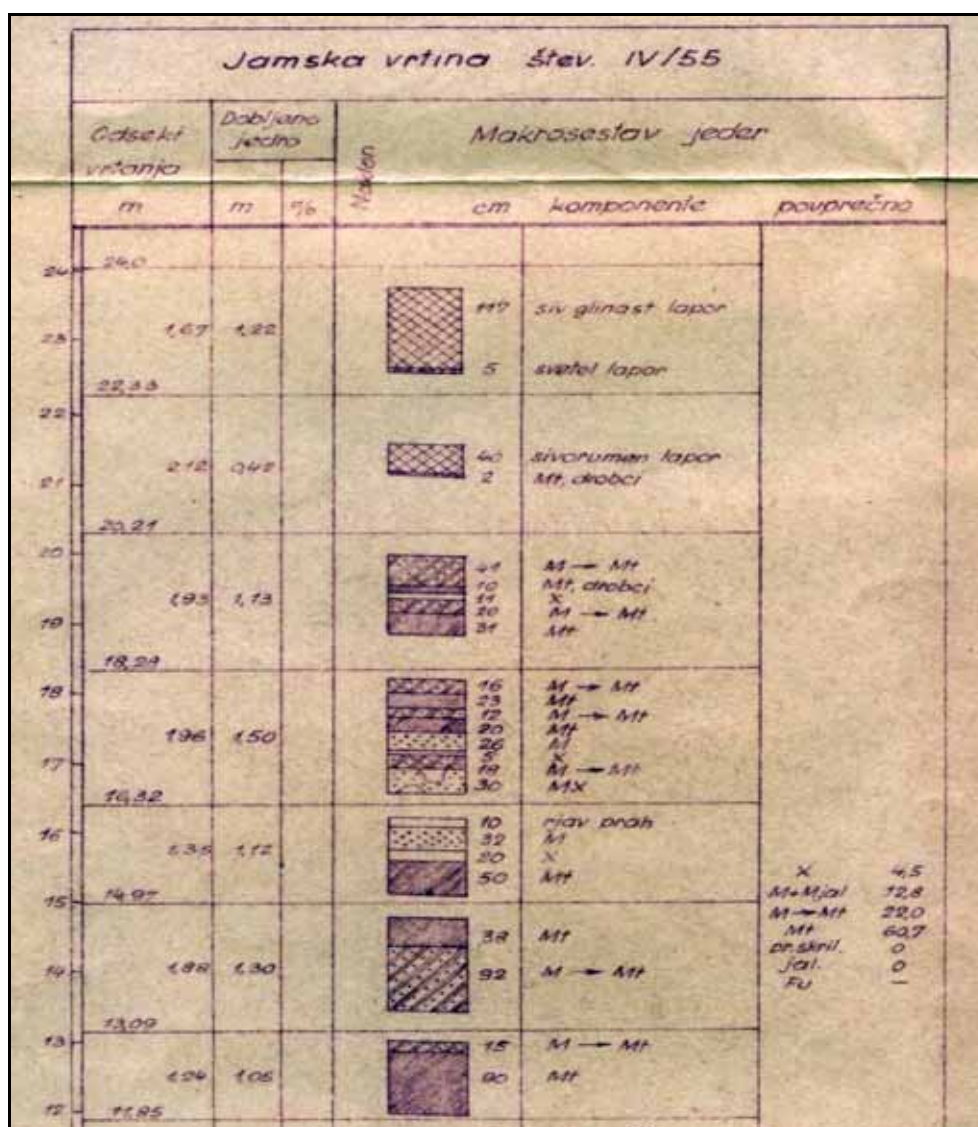
In 1955, HAMRLA carried out a petrographical seam profile analysis (macro-petrographic logging) of lignite cores from six boreholes (Ia/55, IIa/55, III/55, IV/55, 35/55, and 36/55) situated in the E part of the coal mine (HAMRLA, 1955). The total length of the logged cores amounted to 496 m. For the reader, a comparison between HAMRLA's macro-petrographic lignite logs (**Fig. 3.3**) and macro-petrographic logs as recorded in the 1990s may be interesting (**Chap. 6.3.1**, and **Figs. 6.3–6.6**). On the basis of his logging, HAMRLA estimated the macro-petrographic composition for each quarter of the lignite seam. According to his calculations, xylite content decreases from about 20 % in the lower two quarters of the seam to 8 % in the upper quarter. The brownish variety of the “barski premog” (fine-detrital matrix coal) predominates throughout the seam, with its portions varying between 50 and 56 %. Portions of the moderately and the strongly gelified lignite (“velenjit”), increase upwards from 8 % in the lowermost quarter, through 20 and 30 % in the middle two quarters, to 35 % at the top of the seam. Microscopically, according to HAMRLA's table from 1957 (his manuscript archive), the “velenjit” is predominantly (almost 80 %) composed of gelified plant tissues (texto-ulminite), whereas brownish lignite or a “normal” fine-detrital matrix coal is composed of true detritus (attrinite and gelo-detritite).

In the 1960s, petrographic and other studies of Slovenian coals were mainly related to tests of the suitability of coals for different upgrading techniques. Briquetting was one of them. In this context, the Velenje lignite was studied by ČEBULJ & GERMOVŠEK (1965), who investigated 21 samples representing the middle and the upper part of the 61 m thick lignite seam profile drilled by the P-IIIb-4/64 well. Macro-petrographic descriptions and micro-petrographic characteristics of samples (excellently documented by photos) were treated in terms of coal facies and interpretation of environments. The latter were interpreted as alternating forest swamp and moor (a.c.<sup>15</sup>: bush, moss and herbaceous) environments, with alternating anaerobic (prevailing), aerobic (subordinate), and transitional conditions during the stages of humification and early coalification. Aerobic conditions were ascribed to facies with outstanding contents of eu-detrite (a.c.: attrinite) and fusinite. The best properties referring to briquetting were found for xylite, which is, however, a subordinate component. A suitable moisture content of lignite to be briquetted was ascertained to be 14–16 %. The prevailing detrital (matrix) coal was found as not suitable for briquetting. Interesting is the statement of the authors that the “unsuitability for briquetting results from the chemical composition of coal, which is characterized by the presence of Ca humates” (a.c.: chelates). It can be therefore inferred, that most probably gelification effects, such as brittleness and lack of resinous components were the crucial reason for poor briquetting properties. Similar relations were found recently for the Lower Rhine lignite in Germany by NAETH et al. (2004).

In an overview work describing petrology and petrography of coals in former Yugoslavia, DIMITRIJEVIĆ & NIKOLIĆ (1980) characterized the Velenje lignite to be composed of 58 % of “detrite-texto”, 38 % of “textite-gelo” and 3 % of fusite (in terms “As in use in former East Germany”). In nowadays terms for macerals of brown coals and lignites (TAYLOR et al., 1998, p.180, tab.4.3 – after ICCP 1971, 1975, 1985), “detrite-texto” corresponds to humodetrinite, whereas “textite-gelo” to ulminite. Thus, the portions of attrinite versus densinite and ulminite versus textinite remain unclear.

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<sup>15</sup> a.c.: authors' comment



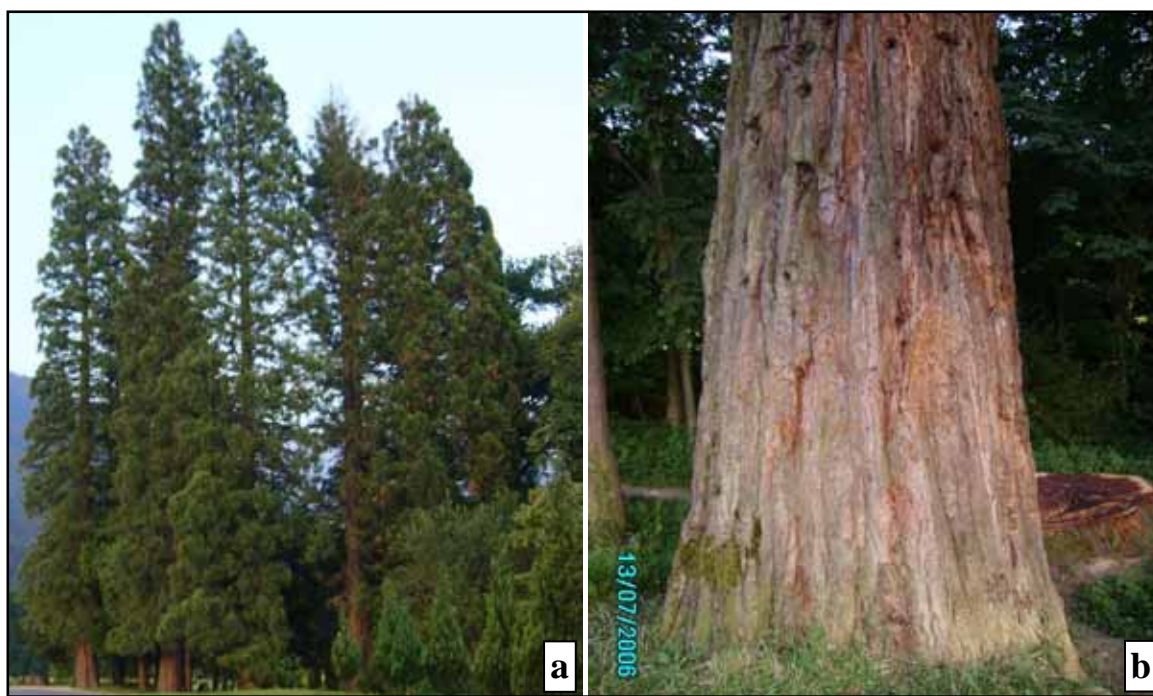
**Fig. 3.3:** Petrographic lignite seam analysis by HAMRLA from 1955 (upper quarter of the seam in the IV/55 borehole). Abbreviations: X - xylite; M - brownish fine-detrital lignite; Mt - black lignite; Fu - fusite; lapor – marl; skril. – shale; jal.: dirt band. Note the average composition on the lower-right (in %), and the high percentage of black lignite!

### 3.2. Estimation of coalification rank by reflectance of huminite

HAMRLA (1985/86) studied the rank of coals in Slovenia, and measured also huminite reflectance of the Velenje lignite. It can be inferred from this paper that in the frame of a regional coalification study involving 50 samples from 37 localities (3 of them from outside of Slovenia) mostly only one block sample was measured per a locality. For the Velenje lignite (from the Preloge sector), he published a mean huminite reflectance value ( $R_m$ ) of 0.24 % (for details see **Chap. 7.1**).

### 3.3. Palynology

In the 1960s and the 1980s, stratigraphy of the Pliocene strata of the Velenje basin was studied by pollen analysis by ŠERCELJ (1968, 1985/86). He mentions that the first palynological investigation of a “mixed” (composite) lignite sample was carried out by Nikola PANTIĆ (in WEYLAND et al., 1958) and that in a poorly preserved pollen assemblage, twenty taxa were identified. In the 1960s, Alojz ŠERCELJ studied only the shallow sediments above the seam with remnants of mastodons, and ascertained their Villafranchian (Pleistocene) age. In the 1980s, he studied both, samples from the lignite seam (including its transition to the clayey floor) and samples throughout the overburden sediments in a thickness of 350 – 450 m. He found out that coniferous “Taxodium” flora (*Taxodium*, *Sequoia*, *Cupressaceae*, *Sciadopitys*) was predominant during deposition of the floor rocks, represented the main peat-forming biomass, and was still characteristic of the time of deposition of the lower part of the sediments overlying the lignite seam. An example of a recently growing *Taxodium* is shown in **Fig. 3.4**. With time, coniferous flora was gradually replaced by foliage plants (*Fagus*, *Carya*, *Pterocarya*, *Engelhardtia*, *Juglans*, *Nyssa*, *Illex*, *Zelkova*, *Ostrya*, *Castanea*, *Carpinus*, *Quercus*, *Tilia*, *Ulmus* etc), in a final stadium with predominance of the beech tree (*Fagus*) characterizing the uppermost part of the Pliocene succession before transiting to Pleistocene sediments with mastodon remnants and arctic pollen elements (*Selaginella*).



**Fig. 3.4:** a) *Sequoias* at the Predvor lake (N Slovenia, north of Kranj) planted in 1840. b) Highly resistant and tough basal part of a *Sequoia* trunk, at the bottom more than 2 m in diameter.

In comparison to other intermountain lacustrine Pliocene coal deposits in Slovenia, e.g. Kanižarica and Kočevje studied in detail by BUDNAR–TREGUBOV-a (1961), ŠERCELJ (1985/86) pointed out that the Pliocene flora was not spatially uniform but typically diversified from one site to another. Both, the Kanižarica and the Kočevje basin, involve several brown coal seams (up to some metres thick), which are, among others, also petrographically very different, from dark homogeneous (detrital) to xylite-containing

heterogenous seams. To a considerable degree, the heterogeneity can be attributed to bulk temporal, spatial and typological floristic variations. As pointed out by BUDNAR–TREGUBOV-a (1961), changes in contributions of coniferous versus foliage floral precursors were crucial for controlling petrographic (lithotype) differences between coal seams as well as within themselves.

In Velenje, the most complex palynological study of the lignite was performed in the late 1990s by Angela BRUCH (in HEMLEBEN, 2000), the same author who had previously studied also the Zasavje coal seam (BRUCH, 1998).

### 3.4. Geochemistry

In the frame of a geochemical study of coals produced and explored in Slovenia in the 1980s, PIRC & ŽUŽA (1989) characterized also the Velenje lignite by the analysis of minor (Si, Al, Fe, Ca, ..., Cr (as oxides)) and 18 trace elements. The studied bulk samples represented “run-of-mine” lignite in September and August 1982 from the Preloge and Pesje sectors. The geochemical composition of these samples was analyzed by OES<sup>16</sup> using coal ashes (at 400 °C). PIRC & ŽUŽA (1989) concluded that the ash of the Velenje lignite is in general poor in trace elements and that most element contents are close to the Clarke (average) values for world coal ashes. According to the Clarke values, only Mn and Zn were detected to be considerably enriched in the ash of the Velenje lignite.

### 3.5. Quality of coal

The quality of coal has routinely been analyzed since the beginning of coal mining in Velenje and is documented and interpreted by the VLM. As summarized by VEBER & DERVARIČ (2004, p.19), the database of chemical parameters involving the determination of moisture, ash, volatile matter, C-fix, coke and sulphur contents and the determination of calorific value consists of more than 1600 samples (**Tab. 2.2**).

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<sup>16</sup> OES: optical emission spectroscopy

## 4. REASONS TO STUDY THE VELENJE LIGNITE – THE AIMS, INTERESTING ASPECTS AND HYPOTHESES

The motivation to study the Velenje lignite petrologically arises from scientific and applied problems. Consequently, the aims of the present study can also be roughly differentiated into those of a fundamentally scientific character and those of applied character. The two aspects are complementary and it is a great privilege for a coal geologist to have an opportunity to deal with both of them interactively. Both points of view, starting with the fundamental and followed by the applied, will be briefly commented below. However, in this monograph, much greater weight will be given to the fundamental aspects.

Among the factors, which make the Velenje lignite unique and a rewarding object for coal geological investigations are:

- its exceptional thickness,
- its formation in a sedimentary basin characterized by very high subsidence rates
- its formation in a Ca-rich environment

Obviously it is important to investigate the processes which controlled the accumulation of the biomass, the type of peat-forming environments (low-lying versus raised mire types) and the processes of peat to lignite formation.

### 4.1. Thickness

Maybe the first basic reason to study the Velenje lignite seam by means of coal petrology lies in its extraordinary thickness which reaches more than 150 m. Whereas the bowl-shaped seam is very thick, its lateral extent is quite restricted (about 11 km<sup>2</sup>), and the area where the seam is more than 80 m thick is less than 4 km<sup>2</sup>.

For a comparison, thicknesses of some of the thickest seams worldwide are listed below as follows (from THOMAS, 1992):

- **Rhenish lignite** (low in ash and sulphur) in Germany (the world's biggest lignite producer) – several seams up to 90 m;
- **Geiseltal** (high ash) brown coal in Germany – a single seam up to 100 m;
- **Belchatow, Lower Lausitz, and Turoscow** lignites (high ash) in Poland – several seams up to 60–70 m, in Belchatow also more than 100 m;
- **Elbistan** lignite (high in ash and sulphur) in Turkey – a single seam up to 85 m;
- **Gippsland** lignite (low in ash and sulphur) in Victoria in Australia – principal seams reaching 300 m,
- **Singrauli** bituminous coal (high ash) in N India – one exceptional seam up to 135 m;
- **Liaoning** bituminous coal (low in ash and sulphur) in China – some of numerous coal seams are more than 100 m thick.

All listed lignites are of Tertiary age, whereas bituminous coals from China and India are Paleozoic and Mesozoic in age.

The significant compaction of peat and coal and the significant mass loss during coalification has to be considered, if the thicknesses of coals of different rank are compared. MCCABE (1991) mentioned that estimates for compaction ratios from peat to coal range from 1.4 : 1 to 30 : 1 (after RYER & LANGER, 1980). According to TAYLOR et al. (1998, p.25), the compaction ratio is generally considered as 6 (peat) : 3 (soft brown coal) : 1 (bituminous coal). Taking into account the latter approximation, the thickness of the Velenje lignite seam (~ 150 m) suggests a peat thickness of at least 300 m, (which would potentially produce a bituminous (“hard” or “black”) coal seam about 50 m thick or less).

The exceptional thickness of the Velenje lignite seam strongly affects the applied mining methods. For example, underground workings of the VLM are considerably concentrated and run almost entirely within the body of the lignite seam. This matter of fact implies the whole complexity of geotechnical problems and mining hazards, as already presented in **Chap. 1.5**.

## **4.2. Regional geological position and basin type**

The Velenje basin is a tectonically controlled intermountain pull-apart basin. It was formed in Pliocene as a result of dextral strike-slip movements along the Šoštanj fault, which is tightly connected to the Periadriatic fault zone. Pull-apart basins, together with graben or rift basins, are characterized by very high subsidence rates (e.g. FLORES, 1989; LAMBIASE, 1990; MCCABE, 1991; SACHSENHOFER et al., 2000-c, 2003; and many others) controlling both, accumulation of inorganic and organic sediments.

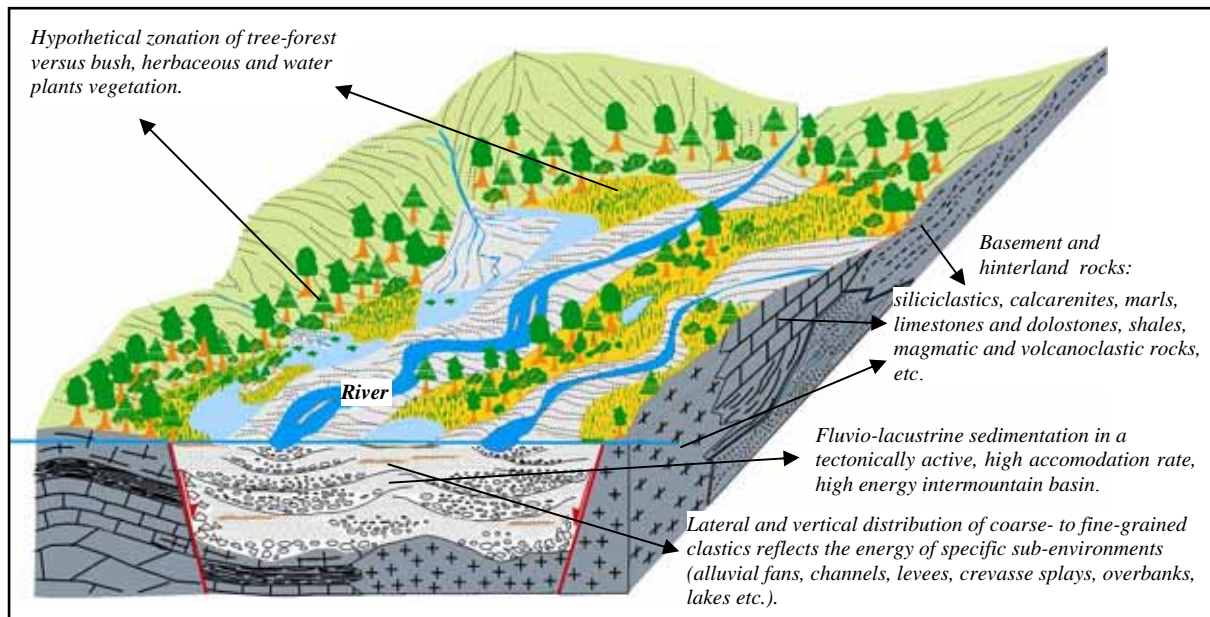
Several coal-bearing pull-apart basins were also formed in the wider area of the Eastern Alps (Austria) during the lateral extrusion in the early and the middle Miocene times (SACHSENHOFER, 2000; SACHSENHOFER et al., 2000-a, 2000-b; GRUBER et al., 2004). Coals in these basins have been intensively studied (GRUBER & SACHSENHOFER, 2001; BECHTEL et al., 2001, 2007-b). The study results have shown that both, the stratigraphic position of the seams within the basin fill and vertical in-seam variations are mainly controlled by high subsidence rates. Most of the basins – but not all – are the result of a single-stage subsidence event and contain a single seam (up to 15 m thick), which was deposited in a transgressive setting during the transition from fluvial to lacustrine environments.

In comparison to the Eastern Alpine basins, the thickness of the main seam in the Velenje basin is significantly higher. Thus, it remains to be investigated whether the huge thickness of the main seam is due to a single or several subsidence events.

**Fig. 4.1** provides a cartoon of a tectonically controlled basin. In the pictured stage of the basin evolution, fluvial activity hinders the formation of an extensive peatland. An extensive seam with few splittings will only form, when high subsidence rates will help to diminish the fluvial influence. Thereafter, peat accumulation will persist as long as subsidence and peat accumulation rates will be in equilibrium. Depending on fault activity, the margins of pull-apart and rift basins might be rather steep (see **Fig. 4.2** for a recent example) and alluvial fans are frequently observed along the fault controlled margins (**Fig. 4.1**).



Examples of recent peatlands are shown in **Figs. 4.2, 4.3, and 4.4**. Both in **Fig. 4.3** and **4.4**, contacts between forested and open-water areas are very distinctive. Forested areas are sites for the formation of xylite-rich coal, whereas open-water surfaces may produce fine-detrital coal.



**Fig. 4.1:** Cartoon showing the facies distribution in a hypothetical fault controlled basin. Typically, fluvial environments prevail during early stages of basin evolution and are later replaced by lacustrine environments. Peat accumulation starts during the fluvial stage (shown in the cartoon), but lateral continuous peatlands only form at the transition to a lacustrine environment. Peat accumulation continues till subsidence rates exceed peat accumulation rates (see **Chap. 4.3** and **Fig.4.5** for more explanation).



**Fig. 4.2:** Typical topography of a fault-controlled intermountain basin (the Ljubljansko Barje basin; photo by Žiga in Wikipedia): with a flat peatland in the front (ca. 300 m a.s.l) and mountains (Dinarides; Jurassic limestone; ca. 1100 m a.s.l.) in the back. The peat at the surface overlies fluvial to lacustrine clastic sediments up to 180 m thick (MENCEJ, 1988/89). Immediately below the ca. 2-m-thick peat layer there is a snail-rich lacustrine chalk (PAVLOVEC, 1967). The peatland suffered from anthropogenic changes. The building of a water drainage system began 250 years ago and the peat was extensively exploited during the 19<sup>th</sup> century. Today, the area is divided to agricultural pieces of land and to wildlife conservation areas. Peat exploitation is prohibited.





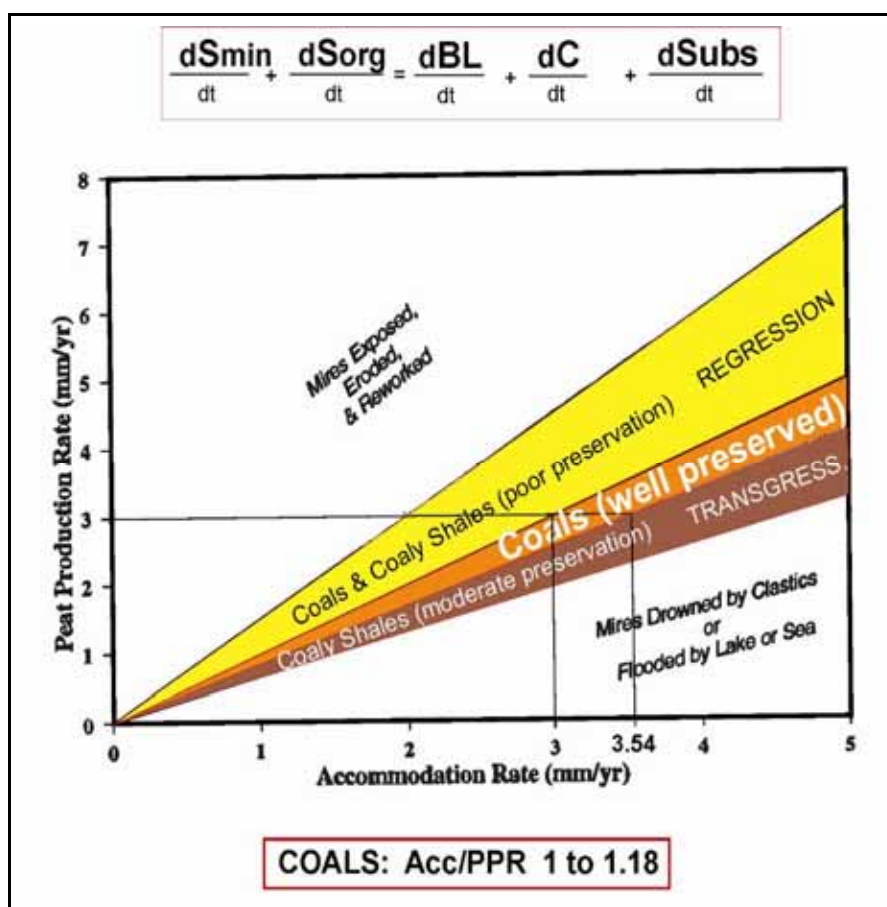
**Fig. 4.3:** Zonal distribution of coniferous-tree, bush-pine, herbaceous and water-plant vegetation along the shoreline of a recent lake with peat accumulation (Lovrenc lakes in the Pohorje Mts.; ca. 1500 m a.s.l.) (see Fig. 2.1 for location of the Pohorje Mts. in the Eastern Alps). Note the peat layer just by the lake shore (below the pine bush).



**Fig. 4.4:** The Everglades, a recent paralic swamp showing mangrove swamps and open-water areas, the latter passing toward the open sea (Gulf of Mexico). Paralic environments occur along the coastlines such as the Eastern USA. (Photo by Yann Arthus BERTRAND; <http://www.yannarthusbertrand.org>).

### 4.3. Accumulation of biomass

Accumulation of biomass and its preservation in the geological milieu are controlled by the equilibrium between peat production and creation of accommodation space. BOHACS & SUTER (1997) tried to quantify this relation (**Fig. 4.5**). They defined a peat production rate as the sum of the accumulation rate of inorganic ( $S_{min}$ ) and organic material ( $S_{org}$ ), and an accommodation rate, which is controlled by base level (BL) changes, compaction (C) and subsidence (Subs). The authors state that the ratio between accommodation and peat production rates for optimum coal preservation should be from 1.00 to 1.18. Higher ratios are typical for transgressive settings, where peat accumulation is replaced by the deposition of clastic material. Lower ratios occur in regressive settings, where peat preservation is poor due to the oxidation of biomass.



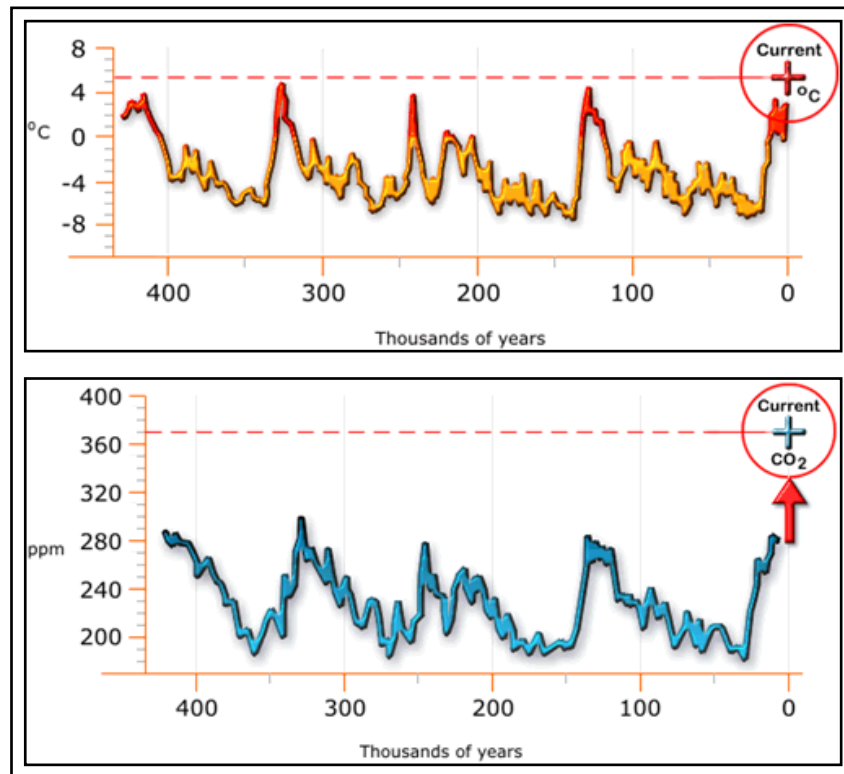
**Fig. 4.5:** BOHACH & SUTER's (1997) diagram showing the relationship between the peat production rate and the accommodation rate decisive for the formation of coals and coaly shales.

### 4.4. Peat growth and development of coal facies

Peatlands form in humid conditions, both in cool and tropical climates. Therefore, coal is not a good palaeotemperature indicator. In general, peat accumulation in cold climates is slower than in warm climates. However, the decay of plants is also slower in cool climates. A peat growth rate of 1 mm/a is a realistic value for moderate temperatures, but this value can vary

from <1 to 7 mm/a (BOHACH & SUTER, 1997 – after BOYD & DIESSEL, 1995). McCABE (1984, 1991) gathered data on peat accumulation rates in different areas of the world, which vary from 0.1 mm/a in the high-latitude Yukon delta (Alaska) to 2.3 mm/a in tropical raised swamps in Sarawak (SE Asia).

The 150-m-thick Velenje lignite represents a peat layer about 300 m thick (see **Chap. 4.1**). Acceptance of an average peat accumulation rate of 1 mm/a results in a very rough estimate for the duration of peat accumulation of 300,000 years. This value is in the order of magnitude comparable to a well established 400,000-year period with periodic global climate changes as illustrated in **Fig. 4.6**. Thus, it has to be investigated, whether – apart from tectonic processes – also climatic changes may have influenced the formation of the Velenje lignite seam.



**Fig. 4.6:** Two diagrams showing periodical and coinciding changes of global temperature and CO<sub>2</sub> emissions of the Earth over the past 400,000 years. This time span may be comparable to periods of peat accumulations giving thick coal seams. (Source: Landcare Research Manaaki Whenua -page current 4. Dec. 2007 – <http://www.landcareresearch.co.nz/research/globalchange/...>).

#### 4.4.1. Low-lying mires and raised mires

Peats mainly develop in two distinct topographic and groundwater related settings, namely in environments where the biomass is accumulated near the regional (ground-)water level (low-lying mires), and in environments where the biomass is accumulated above of it (raised mires) (ROMANOV, 1968; McCABE, 1984, 1991; DIESSEL, 1992; TAYLOR et al., 1998; GRUBER & SACHSENHOFER, 2001; CHARMAN, 2002; and many others).

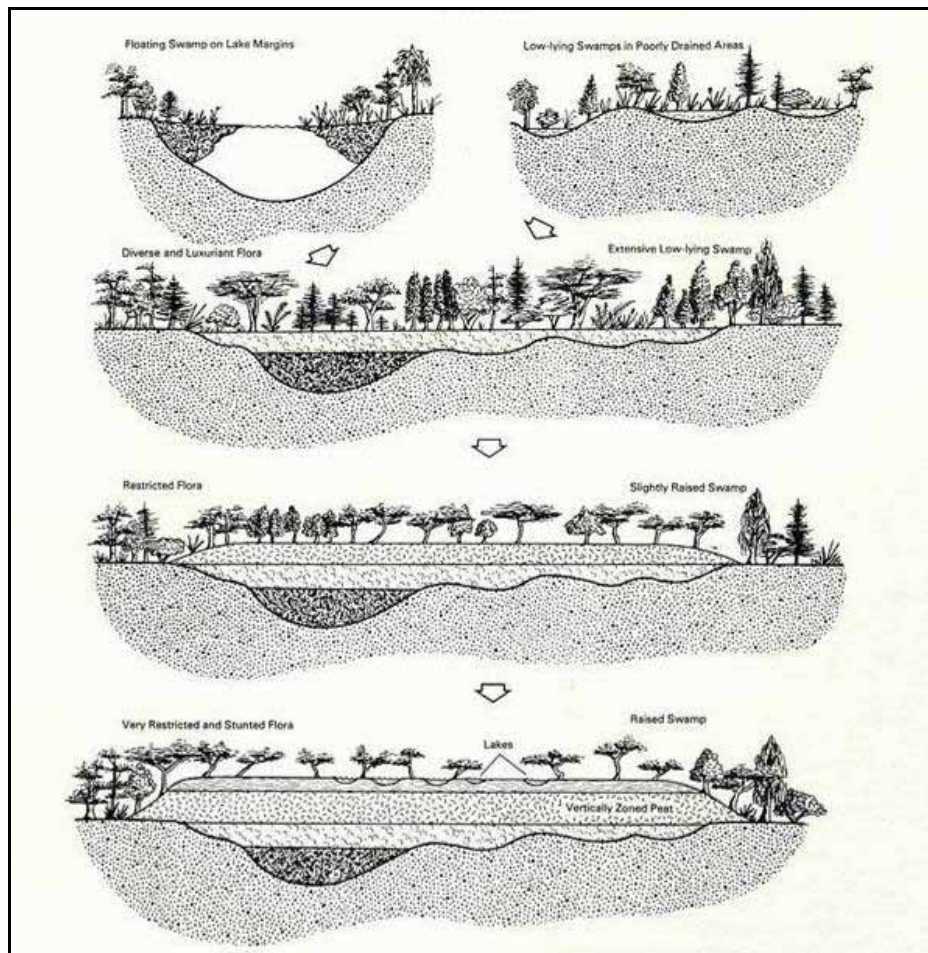
Low-lying (topogeneous) mires (reed moors, fens, forest and bush swamps) were probably more frequent in the geological past. All mineral matter-rich coals can be considered as coals



of topogeneous origin. Low-lying mires receive “inorganic inputs” from outside their confines either by relatively calm groundwater or more turbulent inflowing river, lake or sea waters. Topogeneous percolating waters are hence more (eutrophic) or less (oligotrophic) rich in mineral salts as plant nutrients. Low-lying mires are therefore also termed minerotrophic environments.

In contrast to low-lying settings, peats can grow above the regional (ground)water table if the climate is very humid and so reducing the access of oxygen to decompose the woods. Such rain-fed, ombrotrophic raised mires (also termed bogs) host a less diversified vegetation than low-lying mires. Coals derived from raised swamps are very pure with respect to ash yields and sulfur contents. Mineral matter of these coal types is the inherent one, absorbed from the substratum.

The evolution of many raised mires started in low-lying mires. An evolutionary sequence of a floating mire or a low-lying mire via transitional types to a raised mire is shown in **Fig. 4.7** (after ROMANOV, 1968 – from McCABE, 1984).



**Fig. 4.7:** Evolutionary sequence of different mire types (based on ROMANOV, 1968 – copied from MCCABE, 1984). Peat accumulation commenced in a low-lying mire on a lake margin (upper-most left) or in a poorly drained area (upper-most right). Note the zonation of vegetation types on the lake margin. The following stage is characterized by a low-lying mire with rich vegetation. The two lower cartoons represent a slightly and a strongly raised mire. The raised mires are characterized by a restricted flora, where many trees survive only along the margins of the domed peat.

In view of the high ash yield of the Velenje lignite (**Chap. 2.2; Tabs. 2.1 and 2.2**), an origin in a generally low-lying mire is obvious. However, peat facies and their lateral (spatial) and vertical (temporal) variations still remain an interesting matter of further investigations.

The climate in Pliocene, as inferred from palynological investigations (e.g. WEYLAND et al., 1958; ŠERCELJ, 1968, 1985/86) was colder than in previous Tertiary periods, and hence, as concluded by the mentioned authors, the flora was more diversified. From the mineral matter content (by ash yield), which is well known to decrease from the bottom towards the top of the Velenje lignite seam, it can be inferred that environmental changes at the initial phase of peat formation were by far more dynamic than towards its termination. Depending on groundwater table, parts of biomass were deposited in deeper, and parts of biomass in shallower zones of a depositional milieu.

BREZIGAR (1981) was the first, who recognized the significance of a southward directed alluvial fan, which influenced the basin fill during a very long time. The coarse-grained alluvial fan deposits interfinger with fine-grained basinal sediments and the northern part of the lignite seam (**Fig. 2.4**). The indentation of the elliptical contour of the lignite seam in the north (**Figs. 1.1, 1.3 and 2.2**) is most probably the consequence of this clastic “intrusion” into the peatland. Within the lignite, the alluvial fan resulted in seam splitting and in the occurrence of heterogeneous unsorted coarse-grained clastic rocks (**Fig. 2.4**).

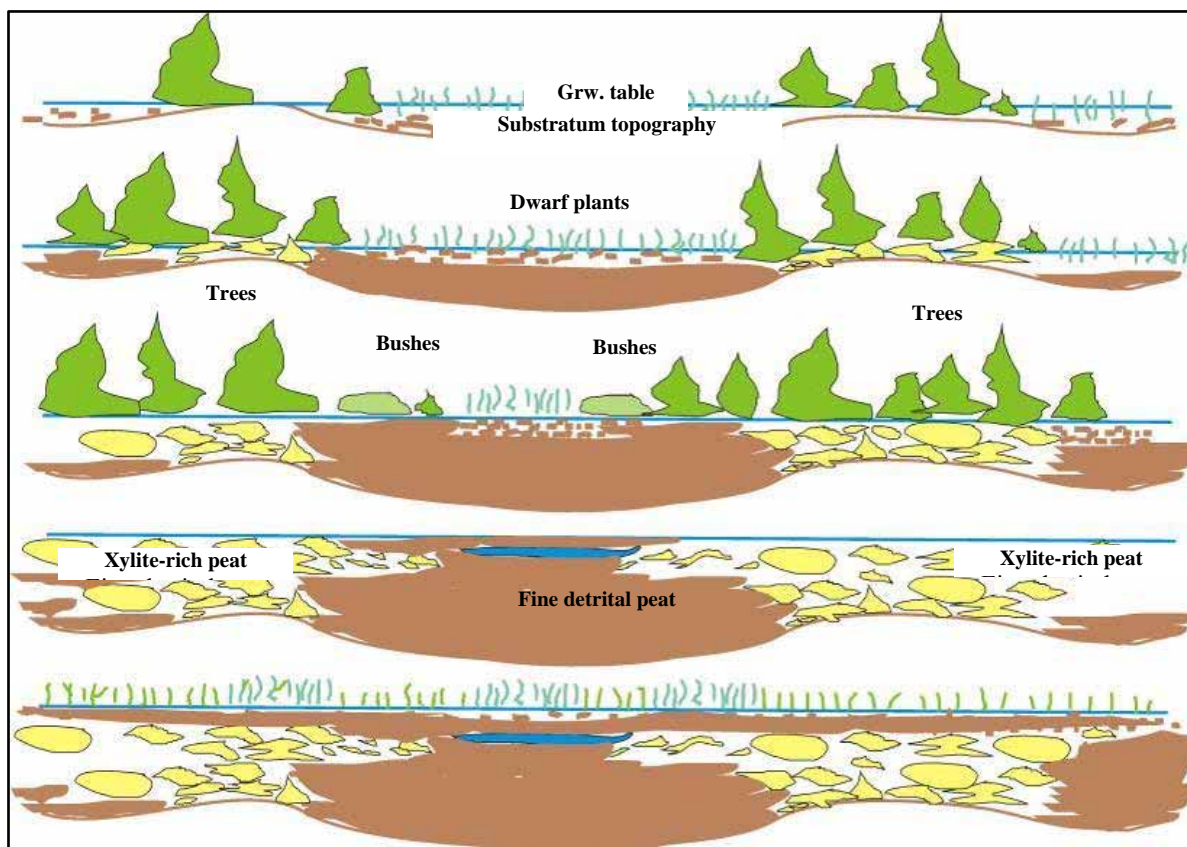
The accumulated peat was thus subjected to different physical (kinetic energy of water, temperature, mechanical properties of vegetal fragments and accompanied components), chemical (redox potential, acidity, nutrient supply), biological (bacterial and fungal activity, diversity and production of vegetation), and sedimentological (deposition of organics versus inorganics) conditions of their transformation and subsequent biochemical coalification.

#### **4.4.2. Topography, vegetation distribution and coal facies – hypothesis of aggradation**

It is hypothetically presumed that the topography of the substratum for subsequent vegetation growth plays an important role in the distribution of tree-rich versus bush and dwarf plant-rich vegetation and that this process results in an aggradational pattern of coal facies distribution (**Fig. 4.8**). This hypothesis is based on the following observations:

- Lignin-rich woody plants such as Tertiary gymnosperms (*Taxodium*, *Sequoia*) give xylite-rich lignite, whereas dwarf plants give rise to predominantly fine-detrital lignite.
- Wood (and xylites) compact to a lesser degree in the same time than fine-detrital material, thus, after accumulation of dead woody plants the surface is expected to be higher than above fine-detrital peat.
- Arborescent flora often flourishes on slightly elevated terrains, including lake margins, whereas dwarf plants prosper on lowlands.

Thus it is expected that an undulating peat surface topography and the related vegetation pattern can persist during the time of peat accumulation.



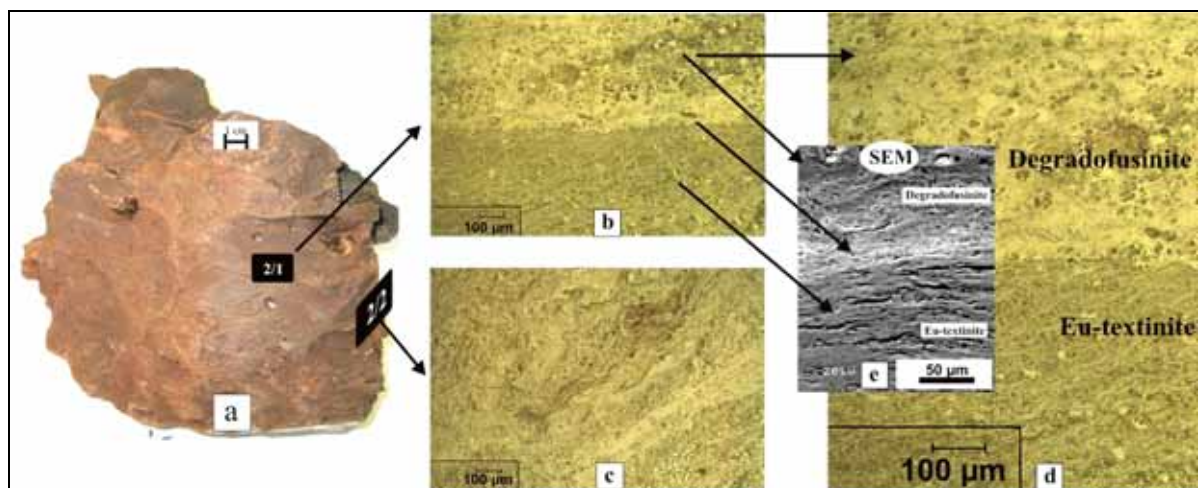
**Fig. 4.8:** Cartoon showing aggradational patterns of tree-rich and dwarf plant-rich areas in dependence from topography and groundwater table. The hypothesis is that vegetation and hence coal facies developments persist vertically due to persisting topographic features which result from compaction differences between wood-rich tree flora and less resistant cellulose-rich dwarf plants, e.g. herbaceous flora. (Situation at the top is the starting one).

#### 4.4.3. Acrotelm and catotelm

Peat bogs can be subdivided into acrotelm (upper peat layer) and catotelm (lower peat layer) (DIESEL, 1992, p.50 – after JACOB, 1961; INGRAM, 1978; CLYMO, 1984; and CHARMAN, 2002, p.45 – after INGRAM, 1978, 1983). Relationships between both layers vary in dependence of fluctuations of groundwater table.

The acrotelm is less than 0.5–1 m thick. It is characterized by variable water content, a fluctuating water table, considerable aeration, high aerobic and anaerobic bacterial activity, and rapid water movement enabling an effective exchange of matter. In hydrogeological terms, acrotelm can be understood as an undersaturated zone in which intensive geochemical reactions are proceeding. The biomass in the acrotelm is subjected to a significant loss due to oxidation (mineralization) resulting in a relative enrichment of the residual organic and mineral matter. In microscopic investigations, effects of oxidation can be observed as the occurrence of degradofusinite, which is oxidized textinite. The formation of degradofusinite is also known to be enhanced by fungal activity. A sharp transition from degradofusinite to textinite is shown in **Fig. 4.9**. Mineralization “at the base” of degradofusinite is visible on the SEM picture as the brightest band. A similar result of oxidation is the formation of macrinite from previously gelified components, but this maceral is very rare in the Velenje lignite.





**Fig. 4.9:** a) Stumpy xylite of uniform appearance; 2/1 and 2/2 are two perpendicular sections; Micro-photos of both sections are shown in b) and c); Note woody cellular structure with different reflectances; d) Detail from micro-photo b) showing a sharp contact between eu-textinite (with corpohuminite) and degradofusinite. A higher reflectance (resulting from a higher carbon content) and higher cell lumens porosity are characteristic for degradofusinite. At very high magnifications, high reflecting oxidation rims can be observed around the empty cell lumens; e) SEM (scanning electron microscope) picture; whereas textinite and degradofusinite are not distinguishable, the bright band indicates enrichment in mineral matter. b), c) and d) are micro-photos made in normal incident light.

The catotelm follows below the acrotelm. It represents a relatively calm environment, anaerobic, with activity of only anaerobic bacteria, constantly waterlogged with only slowly moving waters and low matter exchange. Microbial life can be detected to a depth of 10 m (e.g. BUSTIN et al., 1985, p.21).

Acrotelm processes are presumed to play an important role in the Velenje peat formation. They were probably especially important in places with chaotic tree (xylite) accumulations, which provided a lot of empty space. The products of degradofusinitization (e.g. **Fig. 4.9**) are mostly not visible macroscopically, but true fusite (or char-coal) is. Most often, fusite is observed on the surfaces of larger xylites (**Fig. 6.5**). Fusite originates from the incomplete burning of trees or of already accumulated biomass. Prominent fusite-rich horizons are not known from the Velenje lignite (yet), but local fires, e.g. due to lightning strokes, obviously occurred.

Another phenomenon – calcification of tree remnants – could also take its origin in the acrotelm. Calcification might result from the interaction between Ca-bearing waters and CO<sub>2</sub> emission from the decomposing wood. Alternatively, it might be the result of epigenetic mineralization, connected with Ca-laden waters percolating through tectonic fractures and reaching separate xylite lumps (M. VRABEC, pers. comm.). The latter hypothesis is supported by the observed irregular distribution of calcified xylite. Moreover, a decrease of the frequency of calcified wood pieces with increasing distance from tectonic fractures was sometimes observed during mapping of underground long-walls.



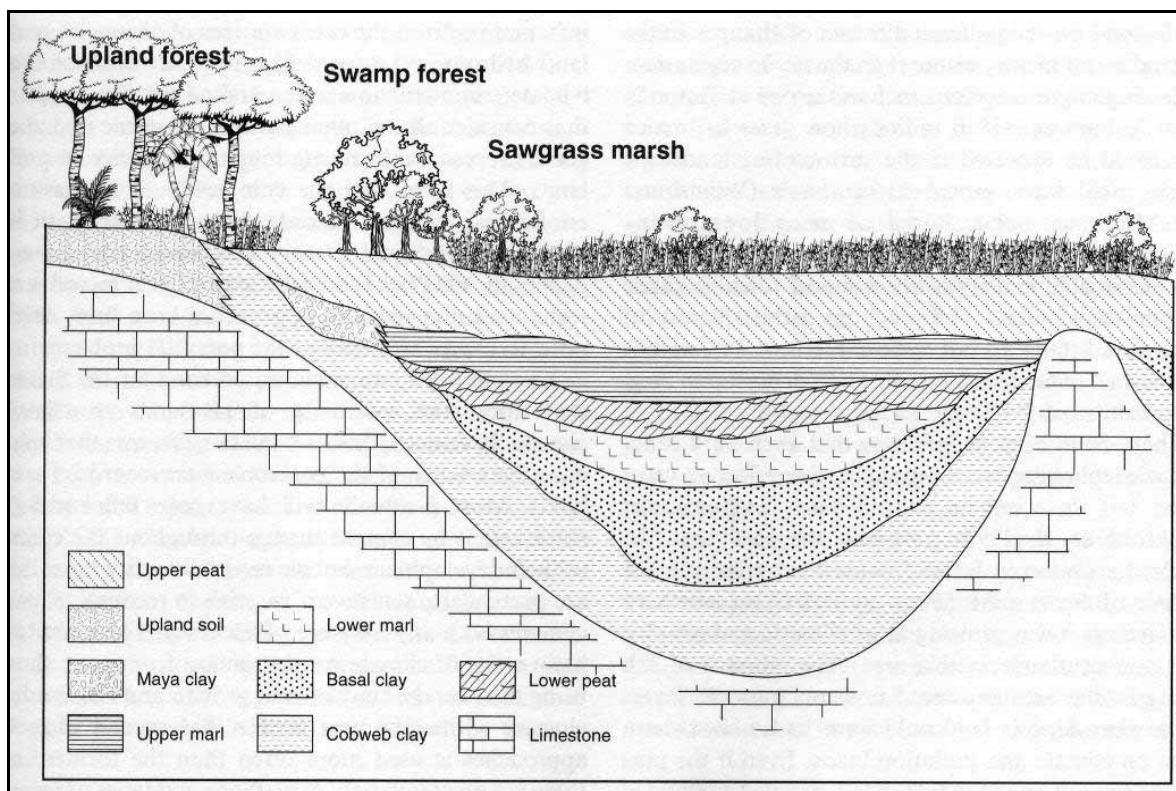
#### 4.5. Ca-rich environment of peat formation and early coalification

Carbonate rocks, comprising Palaeozoic and Mesozoic limestones and dolostones, and Tertiary limestones, marls, carbonate silts, sands and conglomerates, prevail in the pre-Quaternary geological record of Slovenia (e.g. BUSER & KOMAC, 2002; and many earlier authors). This fact also influences coal quality in many coal deposits in Slovenia.

Slovenian coals are typically rich in ash (15–35 %, dry basis), have high sulphur contents (1–4 %, dry basis), and some of them are considerably higher-than-average radioactive. These features indicate that the majority of mineable coal seams in Slovenia evolved from peats that were formed in prevailing low-lying, eutrophic (to mesotrophic), and relatively alkaline mires.

On the basis of coal petrological studies and studies of modern environments it is broadly accepted (e.g.: STACH et al., 1982; DIESSEL, 1992; TAYLOR et al., 1998) that low-lying mires are well fed by plant nutrients. Amongst these, especially Ca, K, N, and P play an important role in both, plant growth and bacterial activity. The latter controls biogeochemical processes, like humification and gelification. Concentrations of dissolved components in lacustrine freshwaters are normally lower than in alkaline sea-waters. However, in non-marine basins, in carbonate terrains, also lacustrine freshwaters can be considerably alkaline due to high solubility of calcite in groundwaters that feed the lake and soak the biomass accumulated. As a result, Ca-characterized lacustrine waters and marine waters can both be alkaline. An example of a recently developing peat accumulation in a limestone-clay-marl geological setting is shown in **Fig. 4.10**.

As cited in TAYLOR et al. (1998, p.37), marine-influenced peats are characterized by neutral to slightly alkaline pH conditions, whereas low-lying mire (freshwater) peats by pH values of 4.8–6.5, and ombrogenous high-moor peats by even lower, 3.3–4.6. On the contrary, Ca-rich waters inflowing from a calcareous basement can increase the pH value even more than marine waters, to a value of e.g. 8.6 (TAYLOR et al., 1998, p.35). The leaching of specific elements, especially of K, from clayey sediments and volcanoclastics can also be a source of alkalinity. Alkalinity is crucial in the diagenesis of peat and coal because it enhances bacterial activity which degrades vegetal matter and has an important role in the reduction of sulphates to sulphides. Ion concentration and hence alkalinity is higher in stagnant waters than in turbulent waters. However, moderate water fluxes as well as slight aerobic environment also act favourably because water influxes import nutrients, and slight oxygen availability enhances bacterial activity. An element showing considerable bacterial activity in coals is nitrogen (N). This element is a constituent of proteins; therefore it is enriched in microorganisms and marine water plants. As a result of the metabolism and after the death of microorganisms, N is concentrated in the sediment and as such a nutrient again enhances vegetation growth and bacterial activity. Coals formed in alkaline environments, either marine or lacustrine, are well known for their increased sulphur contents and some other elements (e.g. by B and P) (DIESSEL, 1992, p.242–243) and already mentioned N, by biochemically more strongly altered (gelified) organic (especially huminitic) components, and, at least in the case of some coals in Slovenia, by an increased radioactivity. The N content was recently studied also for the Velenje lignite on five samples. It was found that the  $C_{org}/N_{tot}$  ratio decreases from 118.4 in the microbially low affected xylite sample down to 34.8 in the microbially highly affected gelified fine-detrital lignite sample (ŠTURM et al., 2009).



**Fig. 4.10:** “Schematic stratigraphy of Cobweb Swamp in coastal Belize. The site is currently forming peat following previous aquatic, peatland and inwash phases (from CHARMAN, 2002, p.175 - after JACOB & HALLMARK, 1996). Horizontal distance is ca. 0.5 km, vertical exaggeration is ca. 80-times – the greatest thickness of sediments overlying the limestone is less than 2 m. Carbonate bedrock and a very close contact between peat and limestone near the right end of the profile resemble to analogous relations in the Velenje basin.

For the carbonate terrains, it is well known (e.g. STACH et al., 1982; DIESSEL, 1992; TAYLOR et al., 1998) that coals contain increased values of Ca – either in their mineral matter, in organo-inorganic complexes, or dissolved in the coal's pore water (WARD, 2002). Coals which are geochemically characterized by Ca (and mineralogically by calcite) are termed “Ca-rich coals”. Among the lacustrine intermountain Neogene coal-bearing basins in carbonate terrains, two basins in SE Slovenia are very typical, the Kočevje (DOZET, 1983; PREMUR, 2005) and the Kanižarica basin (MARKIČ, 1995; PREMUR, 2005). On the other hand, the intermountain basin of Ilirska Bistrica (PREMUR, 2005) in S Slovenia is situated in a terrain, where carbonate rocks are less dominant. The cited basins (see **Fig. 2.1** for locations), in which coal-mining stopped years ago, will be briefly discussed in the next paragraph, and then the story will continue with Velenje.

Both, the Kočevje and the Kanižarica basin are intermountain sub-circular basins (sensu SELLEY, 2000, p.469), formed entirely within the Cretaceous limestone of the Dinaric carbonate platform. They are filled by lacustrine clays and marls and contained (already excavated) up to six coal seams, which were up to several (in Kočevje extremely up to 22 m) metres thick. The coals in both basins were low-rank, very low to medium grade, and sulphur-rich coals. On the dry basis (db), the Kanižarica coals contained on average 2.64 % total sulphur, and those from Kočevje even 4.53 % (MARKIČ et al. 2007; recalculated from RCMWRA, 2002 data). Both were also known by an increased radioactivity, with radiation values between 100 and 500  $\mu\text{R/h}$  (compared to background in other sediments of 5–10  $\mu\text{R/h}$

(OMALJEV, 1971)). In the analyzed ashes from the Kanižarica coals, uranium (U) content of 250 ppm (ca 10 times greater than the “Clarke” world average value for coals) was reported by PIRC & ŽUŽA (1989), whereas thorium (Th) content was found to be in normal limits (K was not analyzed).

Apart from the mentioned intermountain basins, coals with even higher radioactivity and extremely high sulphur contents (as high as above 10 %) are paralic (marine influenced) coals in Istria (HAMRLA, 1959; TAYLOR et al., 1998). These are not only surrounded but are entirely embedded within brackish to marine limestone strata of the Upper Cretaceous to Paleogene age. On the very contrary, in the Ilirska Bistrica basin which is filled by homogenous clays above (and laterally within) the Eocene flysch sequence, the very low grade lignite seam of the Pliocene age contained less than 1 % total sulphur (db).

Geological and geochemical factors outlined above mostly balanced also the development of a peatland and later the peatification/early coalification processes in the case of the Velenje lignite. The Velenje lignite basin is surrounded by carbonates (Triassic dolostones and limestones) to the north and to the west/southwest, more to the north also by the Karavanke tonalite, whereas to the south, it is surrounded and underlain to a great part by Tertiary andesite/dacite and their tuffs, which are interbedded by marls, marly clays and silts (MIOČ & ŽNIDARČIČ, 1978; BREZIGAR et al., 1987). The mentioned volcanic rocks belong to the Smrekovec volcanoclastic sequence (HINTERLECHNER-RAVNIK & PLENIČAR, 1967; KRALJ, 1996), more precisely, to its upper part characterized by originally rhyodacitic magmas (KRALJ – pers. comm. in 2007). A hypothetical speculation regarding the lithology of the regional geological setting is that the carbonate background might be considerably responsible for the enrichment of Ca and Mg ions in the waters soaking the accumulated biomass, and that the alkali elements such as K and Na originating from fine-grained andesite/dacite volcanoclastics to the south of the basin represented important nutrients.

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What are the reflections in petrological – i.e. petrographical, mineralogical and geochemical characteristics of the Velenje lignite related to geological considerations outlined in the above chapters will be the core theme of the continuation of this monograph. Study of the Velenje lignite after 1992 will be mostly dealt with. Investigation methods will be outlined first in **Chapter 5**. These will be followed by a detailed description of methodological approaches and results of petrographical (**Chap. 6**), rank estimation (**Chap. 7**) and inorganic geochemical investigations (**Chap. 8**). The monograph will end with the final discussion (**Chap. 9**) and an epilogue (**Chap. 10**). In the final part, also the results of supplementary studies such as of palynology, organic geochemistry, and of isotopic geochemistry, which have been conducted by colleagues during the last 15 years, will be taken into account to additionally clarify the complexity of the entire lignite genesis in the Velenje basin.

## 5. METHODS OF PETROLOGICAL AND GEOCHEMICAL INVESTIGATIONS OF THE VELENJE LIGNITE AFTER 1992

In order to petrologically characterize the Velenje lignite and to interpret its genesis, conventional methods have been used, including macro- and micro-petrography, grade and rank parameterization, inorganic geochemistry, and mineralogy. In this chapter, only a brief overview of the petrological investigation methods will be given since they are presented in more detail in the chapters dealing with different objects and types of the lignite characterization. In parallel studies, palynological, isotopic, and organic geochemical investigations have also been performed, but these were not led by the authors of this monograph.

Our work in Velenje started in 1992 with macro-petrographic logging and sampling of the lignite core in three structural boreholes, P-9k/92, P-8z/92 and P-12o/92 (**Chap 6.3.2**). Further investigations concentrated on the cores from the first two boreholes. In 1998, also lignite from borehole P-11r/98 was macro-petrographically logged. This borehole-core was thoroughly sampled for palynological investigations performed by Dr. A. BRUCH and Prof. V. MOSBRUGGER (in HEMLEBEN, 2000) from the Institute and Museum for Geology and Paleontology – University of Tübingen. This was not the first palynological study in the Velenje basin, but it was the first systematic one within the lignite seam itself.

In total, 285 metres of lignite cores in four structural boreholes were macro-petrographically logged. After logging and sampling, the entire core and remaining sample material has been archived at the sample depository of the Geological Survey in Ljubljana.

Many more lignite cores were studied from the underground boreholes (73 boreholes, in a total length of 2250 m), mostly in connection with subsequent rock-mechanical, gas sorption, petrophysical and other investigations.

Lithotype variability was studied also by mapping in the underground mine workings, i.e. by mapping road-faces (road-heads) and long-walls (**Chap. 6.3.3**). In total, 200 road-faces were documented, whereas the mapping of long-walls was much less extensive because of worse observation conditions. Underground mapping was not feasible throughout the lignite seam. It was restricted to advancing mining roads and to long-walls in exploitation. Thus, it covers mainly the area of the Preloge sector.

At the beginning, before 1996, lithotype classification for soft brown coals as recommended by the ICCP from 1993 (in TAYLOR et al., 1998, p.280, tab. 5.2) was used for macro-petrographic descriptions. Soon afterwards, a special lithotype classification for the Velenje lignite was developed (MARKIČ et al., 2001) (**Chap. 6.3.1**). This was necessary because the existing lithotype classification for soft brown coals, based mainly on the so called “10 % rule”, was not sufficient for a more detailed characterization, which was needed to study possible correlations with rock-mechanical, gas sorption, petrophysical, and geochemical parameters. The basic idea was to establish such macro-petrographic criteria, which would involve not only quantitative and descriptive criteria but also information about the genesis of

coal, especially of the original peat-forming environments. In this context, since coals, especially the low-rank ones, clearly exhibit detrital character, some principles used in classifications of clastic sediments and sedimentary rocks as e.g. excellently overviewed by SKABERNE (1980-a, -b), have been followed.

Other methods, such as micro-petrography, inorganic geochemistry and mineralogy were applied according to established procedures.

We carried out a systematic micro-petrographical analysis throughout a representative profile of the lignite seam in the P-9k/92 borehole (**Chap. 6.4**). This borehole was drilled in the central part of the basin and penetrated the lignite seam in a thickness of 100 m. The analysis was performed in terms of quantitative maceral analysis according to procedures as recommended in STACH et al. (1982) using polished blocks from 67 lithotype representative interval samples not longer than 2.5 m. An identical maceral analysis was done also throughout a lignite seam profile drilled by the P-8z/92 borehole, which was situated in the northern part of the basin where the seam is highly split and interfingered by non-coaly sediments. This maceral analysis embraced only a thickness of 15 m of lignite from which 13 samples were investigated microscopically.

The microscopical work was performed at the Institute for Geosciences – Mining University of Leoben. On the basis of a systematic quantitative maceral analysis, we applied Diessel's petrographic indices to interpret peat-forming environments (MARKIČ & SACHSENHOFER, 1997).

All 80 above mentioned interval samples from boreholes P-9k/92 and P-8z/92, which were studied microscopically, were also analyzed for ash yield (according to ISO 1171 standard), moisture (ISO 5068), total carbon (ISO 609) and total sulphur contents, and for calorific value (ISO 1928). These analyses were done in the Chemical laboratory of the Secondary School Centre in Velenje led at the time by Dinka PIPUŠ, engineer of chemistry.

Coal rank of the Velenje lignite was estimated by considering different parameters, including huminite reflectance measured on selected (eight) polished blocks (**Chap. 7.1**), gross calorific value (GCV) at the moist, ash free basis of low-ash lignite samples, as well as on the basis of carbon content of low-ash lignite samples at the dry, ash-free basis (**Chap. 7.2**). The mentioned rank-indicating parameters were mostly determined using samples from borehole P-9k/92, but partly also using other sample sets. Bed moisture data from geo-mechanical samples were provided by Dr. Simon ZAVŠEK (VLM). However, it was impossible to obtain data on the original bed moisture or on moisture holding capacity as recommended e.g. by ALPERN et al. (1989).

Inorganic geochemical analysis of lignite (**Chap. 8**) was carried out by the Acme Analytical Laboratories Ltd. (Canada) on 30 samples from the P-9k/92 lignite seam profile. In addition, 9 samples representing floor and roof rocks were analyzed. Inorganic geochemical analysis included the determination of minor ("rock forming") (**Chap. 8.5.1**) and of trace (**Chap. 8.5.3**) elements, whereas the analysis of major elements such as of hydrogen, oxygen and nitrogen was not performed<sup>17</sup>. In addition, total and organic carbon, and total sulphur contents were analyzed on this sample set using a LECO approach. Samples were analyzed as whole lignite samples to avoid transformations due to thermal effects. The results of inorganic geochemical characterization of the Velenje lignite were published by MARKIČ (2006).

<sup>17</sup> Major, minor and trace elements are considered in this monograph sensu DIESEL (1992, p.228, 229, 232). The terms minor and trace elements are also used e.g. by LYONS et al. (1989).

Attention was given to comment inorganic versus organic affinity for the bonding of different elements.

Mineralogical investigations, using X-ray diffraction were made by Miha MIŠIČ from the Geological Survey in Ljubljana only on few samples, especially interesting from the mineralogical point of view (**Chap. 8.5.2**).

In recent years some specific lignite samples were analyzed by scanning electron microscopy (SEM) equipped with electron dispersive system (EDS) at the National Building and Civil Engineering Institute in Ljubljana, where Ana MLADENVIČ was so kind as to give the first author access to the microscope and gave him many instructions.

In 1998 the first isotopic investigations ( $\delta^{13}\text{C}$ ) were performed on different lithotypes. Although only twelve samples were investigated, the results clearly showed significant differences in  $\delta^{13}\text{C}$  isotopic composition among different lithotypes (from -22.6 ‰ for xylite to -27.4 for strongly gelified lignite) (PEZDIČ et al., 1998).

Very pioneering systematic investigations were done in the 2000s in the field of organic and isotopic geochemistry of the Velenje lignite, the first including biomarker analysis and carbon isotopic characterization of coal, wood and cellulose (BECHTEL et al., 2003) and the second (KANDUČ et al., 2005) dealing with carbon and nitrogen isotopic characterization of different lithotypes and recent plants. Both studies considerably contributed to the understanding of specific processes affecting the genesis of separate lignite ingredients, lithotypes and macerals.

The latest isotopic study, analysing for the first time isotopic composition of sulphur in coals in Slovenia, was recently done by ŠTURM et al. (2009). This study included only few lignite samples from Velenje, just to compare them with coal samples from three other localities (Trbovlje, Senovo and Kanižarica).

## 6. PETROGRAPHIC CHARACTERIZATION OF THE VELENJE LIGNITE

Petrographic heterogeneity of coals is studied macroscopically in terms of lithotypes and microscopically in terms of microlithotypes and macerals. It is advisable to study the whole spectrum of petrographical appearance because dimensionally different aspects of coal petrography explain and supplement each other. This is the more necessary, as “there is not a strong correlation between the macroscopic petrography and microscopic data, though certain microlithotypes and macerals have a preferred association with particular lithotypes” (HAGEMANN (1980)). For example, “macroscopic” xylite is always composed of the maceral telinite under the microscope, but small telinite particles are not necessarily identified macroscopically as xylite, but generally as detrital coal. Similar is true for some other correlations e.g. between petrographical and palynological data. Nevertheless palynological data greatly improve and support petrography-based interpretations.

Micro-petrography of coals is well established in terms of maceral/microlithotype nomenclature and classification, although a permanent debate runs about the origin and processes of formation of specific macerals (e.g. SCOTT, 2002). Moreover, the usage of micro-petrographic indices as sole paleo-environmental indicator of peat facies has been criticised. This is supported by a study of WÜST et al. (2001), who investigated facies, stratigraphy and composition of a recent peat accumulation in the tropical Tasek Bera basin (Malaysia). Comparing these results with peat facies reconstructions based on micro-petrographic analysis, the authors found out that the usage of micro-petrographic indicators alone would result in a completely wrong facies reconstruction. For this reason, it is highly recommended to study also coals first macroscopically (in terms of lithotypes) and then microscopically (in terms of macerals). Moreover, seam geometry, the relation with floor and roof rocks, ash yield and sulfur contents have to be considered in peat facies reconstructions. From this aspect, lignites are especially interesting, because they are generally more heterogeneous than higher-rank coals<sup>18</sup> and still exhibit to a high degree the primary features of precursive vegetal ingredients and their stacking pattern.

In the following, the lithotype concept for macroscopic description of coals will be discussed first (**Chap. 6.1**) and a brief description of macerals, concentrating on those in low-rank coals (lignites), will be given thereafter (**Chap. 6.2**). These chapters will be followed by macro-petrographic characterization of the Velenje lignite (**Chap. 6.3**), with special emphasis on a new lithotype classification and codification system, developed specifically for the Velenje lignite (**Chap. 6.3.1**). Examples of petrographic logging and mapping of lignite in borehole cores and in underground mine workings will be described in **Chaps. 6.3.2** and **6.3.3**. Micro-petrographic characterization of the Velenje lignite, results of maceral analysis in two reference boreholes, and interpretation of peat-forming environments will be presented in **Chap. 6.4**.

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<sup>18</sup> The term “higher-rank coals” designates just coals of higher than lignite rank, mostly together sub-bituminous and bituminous coals.



## 6.1. Lithotype concept for macroscopic description of coal

For humic sub-bituminous and bituminous coals (also termed hard coals), the classification of lithotypes is based on well known French-derived terms for “coal ingredients” by STOPES (1919), with a typical suffix “ain”, namely vitrain (bright, lustrous coal), clarain (semi-bright coal), durain (black, dull coal) and fusain (friable charcoal-like coal). To the four cited humic coal lithotypes, two sapropelic coal lithotypes were added later, the cannel coal (characterized by predominance of a maceral sporinite) and the boghead coal (characterized by maceral alginite). With regard to mineral matter content, coals grade into mineral-rich coals (visible inorganic matter) and coaly (carbonaceous) rocks (>50 % mineral matter) of different compositions (STACH et al., 1982, p.171-177; ECE-UN, 1998; TAYLOR et al., 1998).

Because hard coals are often banded, clarain sensu Stopes (1919) was further divided – in so called “German usage” (DIESEL, 1992, p.132) – into clarain (in a narrow sense), duroclarain, and clarodurain. In the Anglo-Saxon countries, especially in Australia and the USA, and also in Canada, a simplified but quantitatively more strictly defined lithotype classification for hard coals was introduced in the 1960s (DIESEL, 1965, 1992; BUSTIN et al., 1985). This often cited classification “as in use in Australia and the USA” differentiates between the bright coal (vitrain like, in bands thicker than 5 mm) and the dull coal (durain like, in bands thicker than 5 mm) as end-members. In between, in bands of less than 5 mm, banded bright, banded, and banded dull coals are differentiated in respect to the predominance of a particular variety. Banded bright coal consists of less than 10–40 % of dull bands, and banded dull coal vice versa. Banded coal consists of bright and dull bands (all thinner than 5 mm) whose portions are between 40 and 60 % each (DIESEL, 1992, p.132). A slightly different classification treating in more detail the thickness of separate bands was previously proposed by SCHOPF (1960) (in BUSTIN et al., 1985, p.55).

The lithotype classification for humic soft brown coals has been accepted by the ICCP as late as in 1993. As evident from **Tab. 6.1** (from TAYLOR et al., 1998, p.280; and after an older recommendation by the ICCP from 1984), this classification is very broad, taking into account only one quantitative criterion, that of 10 % content.

**Tab. 6.1:** Lithotype classification for soft brown coals after ICCP (1993) from TAYLOR et al. (1998, p.280). Older terms (ICCP, 1984) are given in parentheses. The term detrital coal is still frequently used (also in this monograph).

Lithotype Group (constituent elements)	Lithotype (Structure)	Lithotype Variety (Colour – gelification)
<b>Matrix coal</b> <b>(Detrital coal)</b>	Stratified coal	Brown (weakly gelified) Coal Black (gelified) Coal
	Unstratified coal	Yellow (ungelified) Coal Brown (weakly gelified) Coal Black (gelified) Coal
<b>Xylite-rich coal</b> <b>(Xylitic coal)</b>	Contains more than 10 % of xylitic fragments	
<b>Charcoal-rich coal</b> <b>(Fusitic coal)</b>	Contains more than 10 % of fossil charcoal	
<b>Mineral-rich coal</b>	Coal with visible mineral matter	

In addition, the lithotypes in **Tab. 6.1** are not ended by the suffix “ain” as originally proposed by STOPES (1919) for lithotypes of hard coals. Maybe, it would be reasonable to term also lithotypes of soft brown coals with the suffix “ain” as proposed below and in **Tab 6.2** – so:

- Xylain for fossil wood with less than 10 % of surrounding detrital matrix,
- Detrain for matrix (detrital) coal with less than 10 % of xylitic (fossil wood) remains,
- Xylo-detrain, xylo-mid-detrain/detro-mid-xylain, and detro-xylain as the varieties between the above mentioned two end-members with 10–40, 40–60 and 60–90 % of xylitic components,
- Gelain? – a new proposal for homogeneous gelified coal in cases when its origin (either from larger wooden pieces or from dwarf plants and vegetal detritus) is not clear anymore due to gelification, and
- Fusain for charcoal-rich coal – with less than 10 % of other than charcoal components

The above cited lithotypes can be additionally described by colour, stratification (bedding) and degree of gelification (**Tab. 6.2**). Not only detrital coal but also xylite pieces can be distinguished by degree of gelification. In the later case, xylite is black, brittle, with conchoidal fracture, but still showing its outer shape and thus distinguished from the surrounding coal matrix. Moreover, we suggest that fusain could be differentiated into “clasto-fusain” (small char-coal particles spread throughout the matrix coal) and “xylo-fusain”, which is closely connected with xylite, mostly in the form of incrustations and/or composing outer parts of xylites.

**Tab. 6.2:** *Lithotypes of hard coals after STOPES (1919), “as in German usage”, “as in use in Australia and the USA” (from DIESSEL, 1992, p.132), and a proposal for adequate terms of lithotypes of soft brown coals using the suffix “ain” – in all cases without sapropelic coals. Detro-xylain to xylo-detrain lithotypes can also be described with additional characteristics as cited for xylain and detrain (colour, gelification, stratification).*

Lithotypes of Hard coals		Adequate lithotype terms for Soft brown coals using the suffix “ain” - a P r o p o s a l
“Coal ingredients” by STOPES (1919) and division of clarain “as in German usage”	Lithotypes »as in use in Australia and the USA”	
Vitrain	Bright coal	<b>Xylain</b> (brown / black, or ungelified / gelified)
Clarain	Banded bright coal	<b>Detro-xylain</b>
Clarain	Banded coal	<b>Detro-mid-xylain</b> <b>Xylo-mid-detrain</b>
Duroclarain	Banded dull coal	<b>Xylo-detrain</b>
Clarodurain		<b>Detrain</b> (stratified / not stratified; brown / black, or ungelified / gelified)
Durain	Dull coal	<b>Gelain ?</b>
Fusain	Fibrous coal	<b>Fusain</b> (clasto-fusain / xylo-fusain)
Coals with visible mineral admixtures		<b>Carbo-minerain</b>

The classification for lithotypes of soft brown coals as suggested in the above text and in **Tab. 6.2** could be a theme for future discussions within ICCP and TSOP commissions, but in this monograph, we follow the official lithotype terminology for soft brown coals as shown in **Tab. 6.1**. However, for better quantitative description of lithotype heterogeneity, we developed a concept of lithotype components, presented in **Chap. 6.3.1.1**.

Description of coal by lithotypes is valuable because it can involve coal in great and continuous spatial dimensions. Most often, lithotype description represents the initial phase of any coal petrological and related investigations. It is efficient in regard to the costs of the achieved results. Any laboratory work, often very sophisticated but carried out on small samples, is without considerable value if not relied to bulk geological structure of the investigated area. Spatial facies analysis and interpretation of coal genesis are almost unimaginable without lithotype study. Also, a range of problems referring to mining, rock-mechanics and gas-dynamics can be efficiently solved practically *in situ* by lithotype treatment of coal because different lithotypes have different properties. Many technological properties relevant for briquetting, liquefaction, gasification, extraction of a range of chemicals by pyrolysis, as well as for combustion are dependent on lithotypes, or more precisely, the cited properties are often studied on different lithotypes. Special components of coals, e.g. xylite, may be interesting as decorative fossil-wood products. Xylite is also interesting because it is often very clean, almost free of mineral matter and may be resin-rich if derived from coniferous wood. On the other side, xylite pieces and surrounding sediment, either organic or even to a high degree inorganic, may represent local geochemical aureolas in which specific chemical elements may be extremely enriched forming replacements of cellular structures or organo-inorganic complexes (chelates). An outstanding discussion on this theme was published by YUDOVICH (2003). In Slovenia, replacements of fossil trunks by uranium minerals are well known in the Žirovski vrh area in the clastics of the Val Gardena/Gröden formation (BUDKOVIČ, 1980, 1981; DROVENIK et al., 1980; HAMRLA, 1990; SKABERNE, 1995). Further on, lithotype characterization of a coal serves as lithological reference for geophysical measurements (e.g., georadar techniques, wireline logging, etc.). Coal-petrographic data explain the results of rock-mechanical measurements and drilling parameters. Proximate and ultimate chemical coal analyses as well as gas adsorption/desorption examinations are also carried out most often on the basis of the previously described lithotype heterogeneity.

## 6.2. Coal macerals and classification of macerals in soft brown coals

Coal macerals are basic microscopically distinguishable components of coals. Optical microscopy of coal samples is carried out on polished blocks (typically up to around 3×3 cm in size), using, like in ore microscopy, incident (reflected) normal light and most often oil immersion. A speciality of the microscopy of coal and other organic-rich geological materials is the use of blue light irradiation, because some organic substances (e.g. liptinite) exhibit fluorescence. Excellent text-books (STACH et al., 1982; BUSTIN et al., 1985; WOLF, 1988; DIESSEL, 1992; TAYLOR et al., 1998), as well as coal petrography handbooks and classifications published by the International Committee for Coal Petrology (ICCP) and The Society for Organic Petrology (TSOP) provide detailed descriptions, classification schemes and information on the origin of different macerals. State of the art, open questions, problems, and ideas for further research in the domain of coal geology and coal petrology were thoroughly dealt with by eminent authors in the 50<sup>th</sup> volume (special issue) of the International Journal of Coal Geology.

Macerals of coals are divided into three groups: the huminite/vitrinite group, the liptinite group and the inertinite group. In the first group, huminite macerals refer to low-rank coals (or lignites), whereas vitrinite macerals to hard coals, i.e. to medium- (sub-bituminous) and high-rank (bituminous) coals. In most Eurasian coals, either Carboniferous or Tertiary in age, huminite/vitrinite macerals highly predominate over inertinite and liptinite macerals, but the latter are often important as special environmental indicators. They also provide coals with special technological properties. “Normal” huminite/vitrinite-rich coals are termed humic coals, whereas liptinite-rich coals are termed sapropelic coals. In the continuation, within the huminite/vitrinite group, only huminite macerals will be debated, because the Velenje lignite is a typical low-rank coal.

Specific macerals are distinguished in incident light by morphological features and by the intensity of reflectance. In the blue light mode, they differ in fluorescence intensity and fluorescence colour. It is often cited that macerals – as the basic microscopic ingredients of coals – correspond to minerals as basic components of rocks. But the latter are characterized by distinct crystallographic and hence optical properties. On the contrary, macerals are neither optically nor geometrically so clearly distinguishable. The most precisely measurable property of macerals is the reflectance of incident light. However, in coals, reflectance is not only the property of different macerals but also depends on their rank. Because of these reasons, in coal petrography it cannot be avoided that different investigators get somewhat different results. The petrography of coals, both macro- and micro-petrography, always holds some subjectivity of the researcher. Precision, accuracy and practical aspects of quantifying macerals have been tested on the basis of a series of round-robin analyses by the Canadian Coal Petrography Group (CCPG) using fabricated coal samples (BUSTIN, 1991). One of the results of these analyses was that after determination of maceral composition in 200–300 points per polished surface, accuracy of the petrographic analysis does not improve considerably. This experience was mainly taken into account also in our coal petrographic studies. Quantitative maceral analysis is time consuming, and hence quite expensive. Maybe this is one reason, why statistical analyses of sources of variances of petrographic results are almost absent in coal petrographic literature.

The interpretation of quantitative petrographic data is mostly based on grouping genetically and environmentally related macerals (or microlithotypes). Their relative abundance is presented either in triangle diagrams (e.g. HACQUEBARD et al., 1964; MARCHIONI, 1980; LITKE & SACHSENHOFER, 1994) or in a form of facies diagrams using different maceral ratios (“petrographic indices”), like the gelification quotient (von der BRELIE & WOLF, 1981; DEHMER, 1989), the tissue preservation and the gelification indices (TPI and GI) after DIESSEL (1986, 1992), and the vegetation and the groundwater indices (VI and GWI) as proposed and modified by CALDER et al. (1991) and KALKREUTH et al. (1991) (see also **Chap. 6.4.1.4.2**).

Maceral classification for soft brown coals according to STACH et al. (1982) and BUSTIN et al. (1985 - after ICCP 1971 and 1975) is presented in **Tab. 6.3** and was used in our microscopical study of the Velenje lignite. A modified classification, the so called “ICCP System 1994” (SÝKOROVA et al., 2005), was proposed after the end of our study and, therefore, was not applied. Anyway, the new classification introduces new terms only for maceral subgroups and not for macerals. Apart from this, SÝKOROVA et al. (2005) provide a clear, exact and brief systematic descriptions of maceral subgroups, macerals, maceral types and maceral varieties.

Huminite macerals derive from plant tissues, broadly differentiated into “woody” (cellulose- and lignin-rich) tissues and less resistant “soft” (cellulose-rich) herbaceous plants (e.g. DIESSEL, 1992, p.53). Because of higher mechanical strength and toughness of woody tissues, the resulting macerals are relatively big fragments of different shapes. They are termed telinites, which are differentiated into textinites that still exhibit well visible cellular structure (due to lignine-rich cell walls and resin impregnation – especially in the case of coniferous woods), and into eu-ulminites, which are homogeneous, devoid of any cellular structure (unless etched) due to complete humification and biochemical gelification (sensu STACH et al., 1982). Texto-ulminite and ulminite are transitional maceral varieties. Ulminites often derive from foliage tree plants. Other parts of biomass, including bushes, grasses, mosses and other dwarf plants, which are less resistant, tend to disintegrate into humodetrinite. In this context, differences also exist between different kinds of wood – angiosperm woods decay faster than gymnosperm woods and hence humodetrinite-rich coals often derive from angiosperms, as for example proved in a classical example of the angiosperm-derived humodetrinite-rich Tertiary brown coals of the Niederrheinischen Bucht (Lower Rhine Embayment) described by von der BRELIE & WOLF (1981). In humic coals, it is fine detritus that forms the coal groundmass or matrix. Plant detritus transforms by early humification/coalification processes from attrinite, which is characterized by still loosely packed particles (mostly less than 10 µm in size), to densinite, whose name derives from a dense detrital appearance due to considerable gelification. According to DIESSEL (1992), the formation of huminite macerals is interpreted as the vitrinitization path of biochemical coalification.

It is obvious that detrital plant material is easier and earlier affected by biochemical processes than the more resistant woody tissue. However, it is also important to consider that: “In the absence of free oxygen, organic compounds containing the most oxygen are preferentially attacked by anaerobic bacteria” (van KREVELEN, 1952, p.359 – from DIESSEL, 1992, p.52). “This affects the rather resistant but oxygen-rich compounds, like lignin, as much as soft tissues, although it may proceed at a greater rate in the latter” (DIESSEL, 1992, p.52). In the case of the Velenje lignite, this aspect is important, because wood occurs in two macroscopic forms: “normal” brown xylite, and gelified xylite (gelo-xylite). The first type predominates, and the second is especially concentrated in the lower parts of the lignite seam. Gelified xylite in Velenje is typically smaller than “normal” xylite and often occurs in lenses, a few mm thin.

Liptinite (or exinite) macerals represent the most resistant, hydrogen-rich substances and parts of plants, as exines of pollen and spores, resins, cuticles, algae, bark tissues, (probably also oils, animal plankton, bacterial lipids). They are in most cases small and/or thin particles, darker than the surrounding coal material, and spread sparsely throughout the coal under the field of observation. Tiny and/or disintegrated liptinite particles that cannot be identified clearly are termed liptodetrinite. Liptodetrinite is a frequent liptinite maceral in many coals. High amounts of liptodetrinite indicate an open water or fen-type depositional environment. Sometimes, if gelification is high, it is difficult to distinguish gelotelinite (ulminite) from gelodetrinites (densinite). In such cases, the presence of liptodetrinite may help to decide that the host material is detrital. An important diagnostic feature of liptinite macerals is their fluorescence, which is the highest in low-rank coals and decreases with increasing coal rank. Apart from liptinite macerals, only low-rank telinite may exhibit (weak) fluorescence, which results from cellulose or resinous impregnations.

**Tab. 6.3:** Maceral classification for soft brown coals – lignites (from BUSTIN et al., 1985, p.35 - after ICCP, 1971 and 1975; and STACH et al., 1982). *Botryococcus alginite* is added to *Pila* and *Reinschia alginites*.

MACERAL GROUP	MACERAL SUBGROUP	MACERAL	MACERAL TYPE; SUBMACERAL	MACERAL VARIETY
Huminite	Humotelinite	Textinite		A (dark) B (bright)
		Ulminite	Texto-ulminite Eu-ulminite	A (dark) B (bright) A (dark) B (bright)
		Attrinite Densinite		
	Humocollinite	Gelinite Corpohuminit	Levi-gelinite Detrogelinite Telogelinite Eugelinite Porigelinite Phlobaphinite Pseudo-phlobaphinite	
Liptinite		Sporinite		Tenuisporinite Crassisporinite Microsporinite Macrosporinite
		Cutinite		
		Resinite		
		Alginite		<i>Pila</i> -alginite <i>Reinschia</i> -alginite <i>Botryococcus</i> -alginite
		Liptodetrinite Fluorinite Bituminite Exudatinit Suberinite		
Inertinite		Micrinite Macrinite Semifusinite		
		Fusinite	Pyrofusinite Degradofusinite	
		Sclerotinite	Fungosclerotinite	Plectenchymite Corposclerotinite Pseudocorposclerotinite
		Inertodetrinite		

Inertinite macerals originate to the greatest part from woody tissues (fusinite), but also from humose gels (macrinite), fungi (funginite; formerly sclerotinite<sup>19</sup>), and as secondary macerals from liptinitic macerals (micrinite). They exhibit the relatively highest reflectance and – in the case of fusinite and funginite – are well structured. They form by the process of fusinitization, which always needs some kind of oxidation, either by atmospheric oxygen, by oxygen dissolved in percolating groundwaters, or by oxygen derived from bacterial activity (DIESSEL, 1992). In contrast to other macerals, inertinite macerals do not transform considerably during coalification after their formation, which can take place as early as in the peat formation phase. This inertia is also the source of their name. Maceral varieties which exhibit properties between true inertinites and huminites hold the prefix "semi" (e.g. semi-degradofusinite).

Reflectance is basically the consequence of the internal molecular order of the organic matter. It is higher in aromatic (benzene-ring molecules) than in aliphatic substances. It rises with

<sup>19</sup> Sclerotinite is a maceral term, which should not be used anymore as pointed out by LYONS (2004). Former sclerotinite occurs in two forms – as secretinite and as funginite. Cellular funginite is especially common in Tertiary coals, and secretinite in Paleozoic coals.



increasing parallelism in molecular structure orientation and particularly with increasing aromatisation (progressing formation of ring molecules). At the same stage of coalification, (aliphatic) liptinite macerals show the relatively lowest reflectance, huminite macerals a medium reflectance and (aromatic) inertinite macerals the highest reflectance. Chemically, in comparison to huminites/vitrinites, liptinites are characterized by relatively high H/C atomic ratios and low O/C ratios, whereas inertinites are characterized by low H/C ratios and are relatively oxygen rich. Both elementary ratios decrease with increasing rank.

### 6.3. Macro-petrographic lithotype characterization of the Velenje lignite

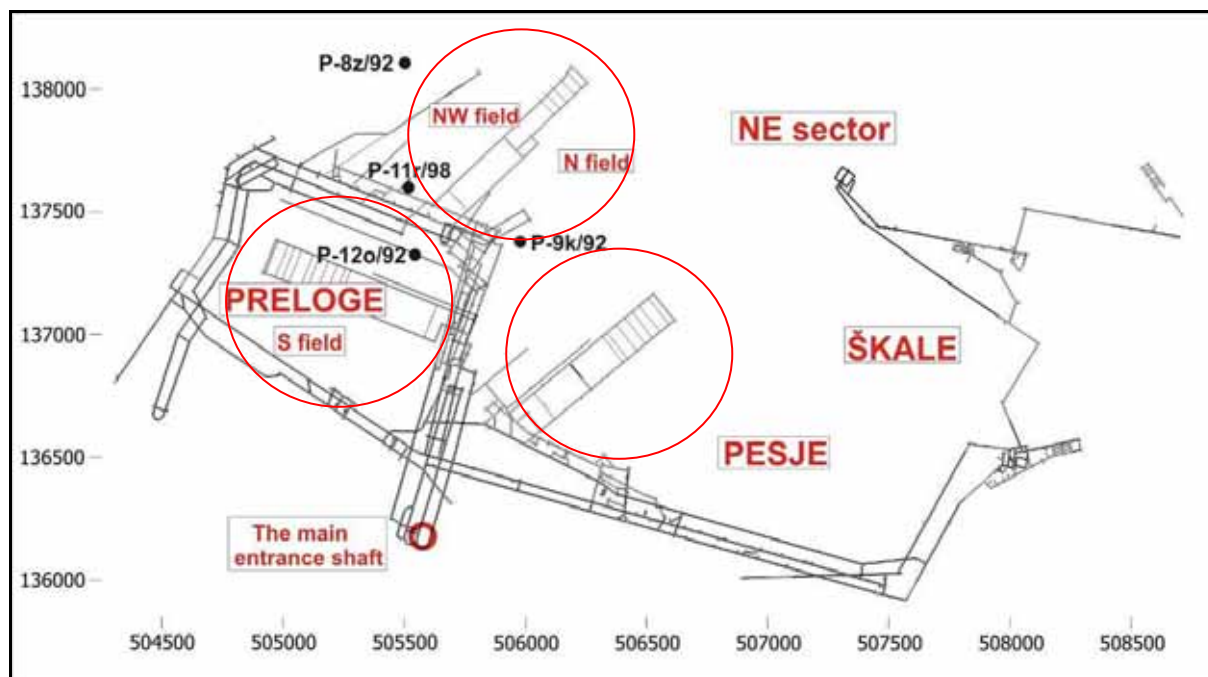
Macroscopic characterization and macro-facies study of the Velenje lignite involved two kinds of study objects: lignite cores from boreholes and lignite surfaces visible in underground mine workings.

- Lignite in borehole-cores was studied from “structural boreholes” drilled vertically from the surface through the lignite seam, and – more often – from “underground boreholes” of very different inclinations (**Fig. 6.1**).
- Macro-petrographic acquisition of data in the underground mine workings was to a great part carried out in the uppermost part of the lignite seam, less than 15 m under the so called “fresh roof”, where no previous mining was carried out. These parts of the seam are in general more problematic from the gas hazard point of view.



**Fig. 6.1:** Lignite core from an underground borehole (JH-3/06). Note differences in “rock quality” (crushed versus compact core). Box length is 1.5 m, core diameter is 54 mm. The right photo shows a ca. 35 cm long xylite-rich core segment with white calcite “inclusions” (borehole JH-3/06 at 62.00 m length).

Borehole-core petrographic data served for forecasting of the lithotype setting expected in a subsequently driven mine workings, while mapping of the mine workings themselves provided an extended insight into spatial (3-D) lignite facies relations. For easier understanding, a map of active mine workings with the mining sectors is given in **Fig. 6.2**.



**Fig.6.2:** Map of active underground mine workings. Three areas of active coal production are signed by red circles. In the NE sector, exploitation ended before the year 2000. Note also the position of four structural boreholes discussed in the text.

### 6.3.1. Lithotype classification and codification for the Velenje lignite

The ICCP (1993) lithotype classification for soft brown coals suggests lignite description by three levels: lithotype groups, lithotypes and lithotype varieties (**Tab. 6.1**). Lithotype groups are characterized by ratios between four genetically and technologically most important components – fine-detrital matrix, xylite, charcoal (“fusite”) and mineral matter. Accordingly, lithotype groups are termed: matrix coal, xylite-rich coal, charcoal-rich coal and mineral-rich coal. Lithotypes are defined by the above mentioned lithotype components and form petrographically distinct stratified and/or non-stratified units such as beds, bands, lenses or irregular masses. Lithotype varieties are differentiated with regard to the degree of gelification and to colour. As already mentioned, the ICCP (1993) classification is quantitatively quite broad. It is based only on the so-called 10 vol. % rule. For example, xylite-rich coal is each coal containing more than 10 % xylite, and charcoal-rich coal is each coal containing more than 10 % fossil charcoal. Mineral-rich coal is defined as coal with clearly recognizable mineral admixtures. Matrix coal is fine-detrital coal with less than 10 % xylite and/or less than 10 % fossil charcoal. Mineral component in the matrix coal is not visible by the naked eye.

According to the ICCP (1993) recommendations and with some specific supplements, also the Velenje lignite can be described by the following features:

- Ratios between fine-detrital matrix and xylitic fragments
- Size, shape, orientation and arrangement of coal components
- Degree of gelification
- Content and occurrence of fossil charcoal (fusite) and of mineral admixtures

- Structural characteristics (lamination, bedding, banding)
- Colour, fissuring, fracturing, jointing, hardness, brittleness, toughness

Lignite is basically considered as a phyto-detrital and biochemical sediment, exhibiting its fragmental pattern and its diagenetic features. Diagenesis of lignite is mostly restricted to the biochemical stage of coalification, i.e., mostly to biochemical gelification (DIESSEL, 1992 - sensu STACH et al., 1982). Compaction and consequent increase in the orientation and packing of the lignite components is an effect of diagenesis as well.

As a sedimentary rock, lignite – particularly its fragmental pattern – can be described in terms of the properties of sedimentary rocks as e.g. defined by GRIFFITHS (1967) (from SKABERNE, 1980). According to this concept, lignite may be axiomatically defined as an aggregate of its constituent elements, therefore having properties according to the following GRIFFITHS's (1967, p.32) expression:

$$P = f(m, s, sh, o, p)$$

“where  $P$  (rock as population) is a function  $f$  of the properties of its elements (mineral particles); and the properties are the kinds and proportions of elements ( $m_1, m_2, m_3, \dots, m_k$  for  $k$  classes of elements), their sizes  $s$ , shapes  $sh$ , orientation  $o$ , and packing  $p$ ”.

In coals,  $m$  refers to coal-forming constituent elements, either to macerals in microscopic dimensions or to **macroscopic constituent elements**. Particle size ( $s$ ), shape ( $sh$ ), orientation ( $o$ ) and packing ( $p$ ) are textural characteristics, while different forms of stratification (including lack of stratification) refer to sedimentary structures. The latter are spatial variations of composition ( $m$ ) and/or one or more textural properties mentioned above.

#### 6.3.1.1. Characterization of the fragmental pattern

The fragmental pattern of lignite is macroscopically described by the size of different **macroscopic constituent elements**, by their composition, and by their shape, orientation, and packing. In our case, it should be pointed out that lignite is mostly described on the surfaces of borehole-cores, on the mining road-faces and on the long-walls. Textural properties and composition are therefore restricted to 2-D (planar) characterization.

At the very beginning of petrographic studies a question arose how to describe the very wide size range of different lithotype constituent elements – especially with regard to the description of ratios between fine-detrital matrix and xylitic pieces – and, at the same time, not to move too much away from the basic lithotype terminology. Finally it has been decided to introduce the concept of **fragmental lithotype components** termed as<sup>20</sup>:

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<sup>20</sup> Note that all components end on “ite”. According to the ICCP rules (e.g. in Stach et al., 1982; Taylor et al., 1998), the suffix “ite” is used for microlithotypes, whereas the suffix “ain” should be used for (macro)lithotypes (see **Chap. 6.1**). However, even in conventional ICCP (1993) classification, the suffix “ite” is used for xylite referring to xylite-rich coal lithotype. In an older working typed version by ICCP from 1984 (**Chap. 6.1**) even the term “fusinitic” coal was used, which is formally unacceptable, because “fusinite” (suffix “inite”) is a maceral. Here, we are not dealing with lithotypes, but lithotype components. Due to the lack of terms for the latter, we decided to keep the suffix “ite”.

- detrite (**D**)
- xylo-detrite (**xD**)
- detro-xylite (**dX**)
- xylite – differentiated into three size classes (**X**, **XX** and **XXX**), and
- fusite (**F**)

**Detrite (D)** (Figs. 6.3-a,b) is composed of fine-detrital homogeneous plant material that represents the matrix between larger fragmental components. In the sense of constituent elements, it is a mono-elemental lithotype component, the elements being very small plant particles that mostly cannot be differentiated macroscopically. Fine detrite is dark brown to black, usually more easily and earlier susceptible to biochemical gelification processes than larger xylitic pieces. Brownish fine detrite may contain thin xylitic bands and/or lenses (Fig. 3.1-c (centre), less than 1 mm thick, but considerably long (or wide). On observation surfaces, they are fibrous in appearance (“lamellar xylite”) and enhance the mechanical strength of fine-detrital lignite. Such fine detrite is marked by the abbreviation **D(x)**. Fine detrite with no thin xylitic remains is brownish-black to black and passes to gelified varieties (Fig. 3.1-d and Fig. 6.3-b).

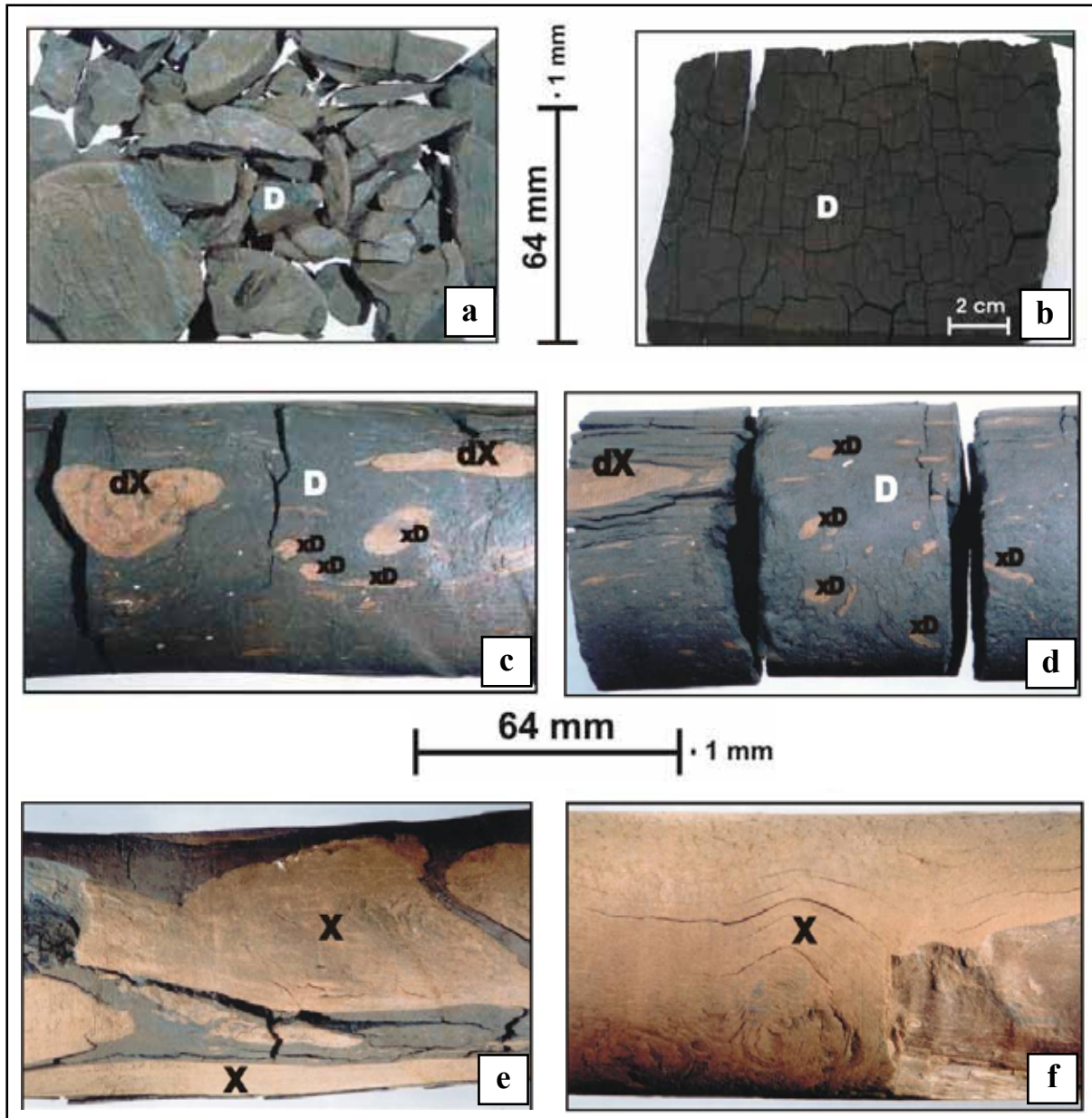
**Xylo-detrite (xD)** and **detro-xylite (dX)** (Figs. 6.3-c,d and 6.4) are lithotype components composed of xylitic fragments and the very closely surrounding fine-detrital matrix. Thus, both components are composed of two constituent elements and are considered as bi-elemental lithotype components. Both, **xD** and **dX** comprise xylitic fragments which are smaller than the borehole-core diameter (which ranges in different boreholes from about 5 to 10 cm). Xylitic fragments of the **xD** component are smaller than half of the core diameter, whereas fragments of the **dX** component are larger than half of the core diameter. If **dX** and **xD** components are considered together, these are signed as **dXxD** or **XD**. The latter is termed as xylite-detrite<sup>21</sup>.

**Xylite (X, XX, XXX)** is a widely used synonym for large brown pieces of wood (branches, stems, stumps, trunks) lying within fine-detrital matrix. Xylite as the lithotype component is considered here as the mono-elemental one. It is divided by the size into three groups. In the case of borehole-cores, “xylite” encompasses all pieces that are larger than the core diameter (Figs. 6.3-e,f and 6.4). Such pieces are signed by **X**. In the underground road-faces and long-walls, where lignite is observed in larger dimensions, **X** pieces designate xylitic fragments up to ca. 0.5 m long, whereas larger ones are termed as **XX** (between ca. 0.5 and ca. 2 m) and **XXX** (>2 m).

**Fusite (F)** (Fig. 6.5) is a synonym for fossil charcoal. It is silky black, needle-shaped, softly fibrous and very porous. Quantitatively it is a rare component in coal. Most often it is not quantified, but only described as one of the ingredients present. Fusite occurs in the form of individual particles or encrustations on xylites.

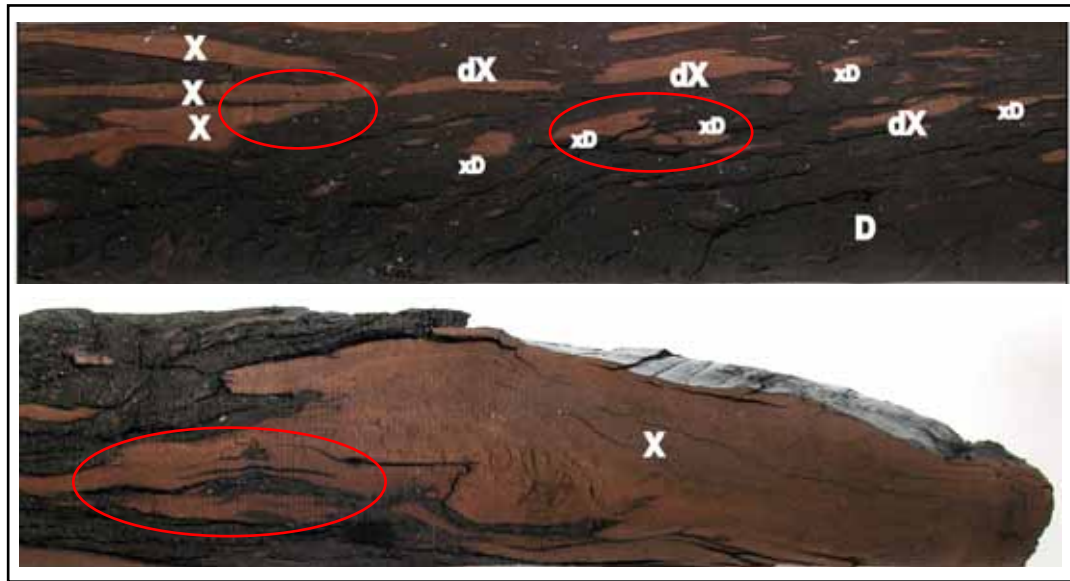
A schematic presentation of lithotype components and the nature of fragment-supported versus matrix-supported fabrics in the borehole-core dimensions is shown in Fig. 6.6, whereas the quantification of the lithotype components is in detail presented in Fig. 6.7.

<sup>21</sup> The term »xylite-detrite« is used in a somewhat similar way as for example the term “silt-clay” for the fine-clastics when it is difficult to decide which component prevails. However, for the silt-clay, another expression also exists, that is “mud”. Unfortunately, this is not the possibility in the case of lignite, where we only have two operative terms –xylite and detrite.



**Fig. 6.3:** Lithotype components of the Velenje lignite as visible in a horizontally drilled borehole-core: **a)** and **b)** **Detrite (D)** forms fine-detrital lignite as a whole. It is typically crushed (**a**) and cracked due to desiccation (**b**) (see also fine-detrital lignite in **Fig. 3.1**). **c)** and **d)** **Xylo-detrite (xD)** composed of xylitic pieces smaller than half of the core diameter, and **detro-xylite (dX)** composed of xylitic pieces bigger than half of the core diameter, both within fine-detrital matrix. **e)** and **f)** **Xylite (X)** as xylitic pieces bigger than the core diameter (**e**), and extending over the entire core dimensions (**f**). Note also the scale-bar of 64 mm, which corresponds to the core diameter.

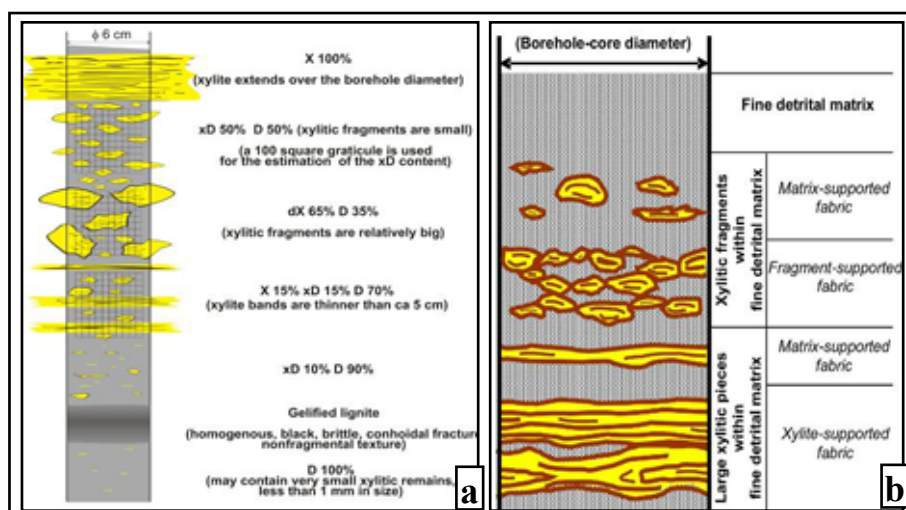




**Fig. 6.4:** Similar as Fig. 6.8 – X, dX and xD components within fine-detrital matrix D. Note fragment-supported fabrics within red ellipses. In the lower core, core loss due to loose adhesion between xylite (note the slide surface) and the matrix can be seen, whereas adhesion is better to the left due to interfingering between xylite and matrix.

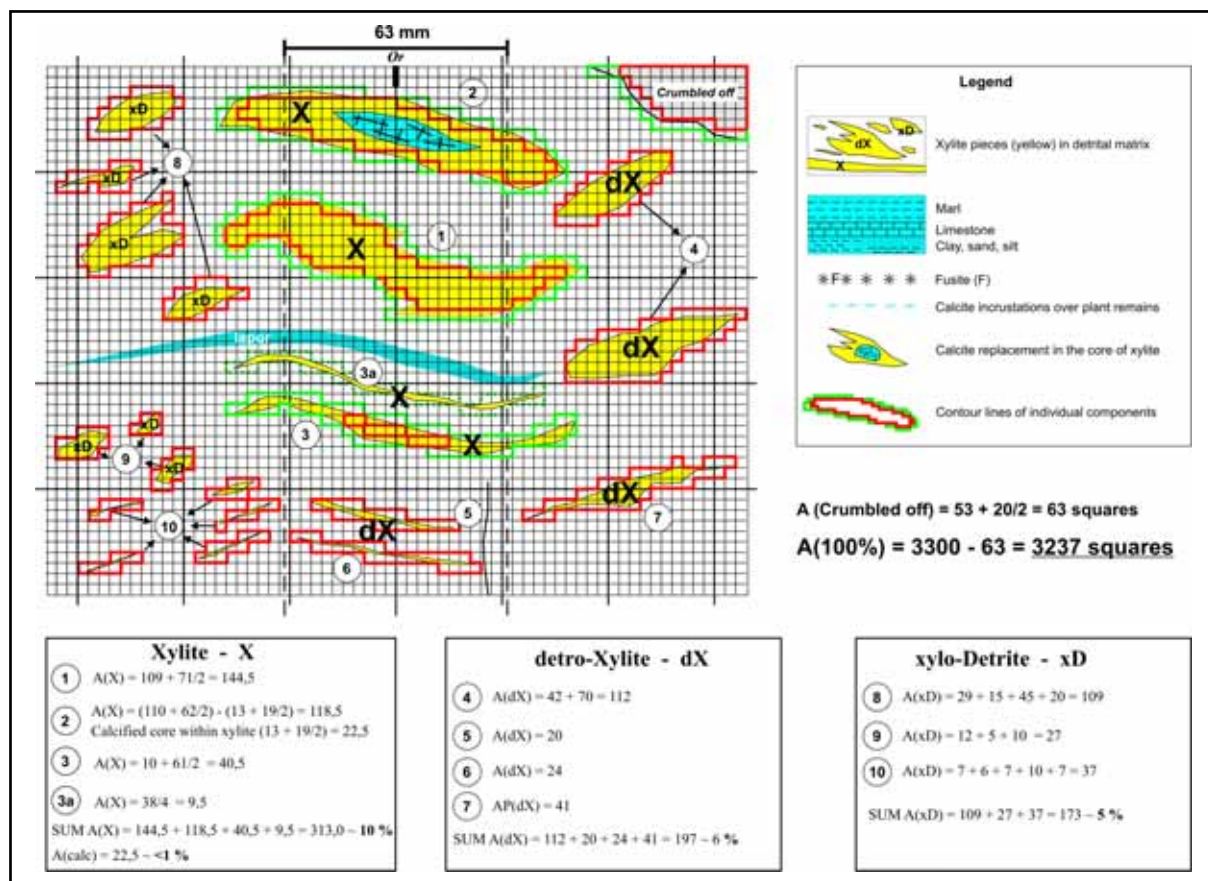


**Fig. 6.5:** Fusite (F) or “fossil char-coal”. It often occurs as incrustation over the outer part of xylite.



**Fig. 6.6:** a) Fine-detrital matrix, xylitic fragments and larger xylitic pieces as lignite-forming constituent elements. b) Matrix-supported and fragment (xylite)-supported fabrics are distinguished. In both sketches the width of the graphical columns symbolises the diameter of a borehole-core.





**Fig. 6.7:** Quantification of contents of lithotype components X, dX and xD with the aid of a 3×3 mm square grid. Other components, inclusions and dirt bands are estimated in a similar way. The whole area for estimation – A (100 %) – comprises 3237 squares (3300 - 63 of the small area which is crumbled off). Squares within the red line are counted as 1, whereas those between the green and the red line as a half (½). Result of the quantification is the following: X content 10 %, dX 6 %, xD 5 %, marl band and calcification within the xylite comprise 3 %, and the rest – 76 % – is fine-detrital matrix D (all in % by area).

In the quantification procedure of the lithotype components (**Fig. 6.7**) it is important to take into consideration that the components may be composed of either one or of two constituent elements. As already discussed, detrite (D) and xylites (X, XX and XXX) are treated as mono-elemental lithotype components. In quantitative estimations, these components are “counted” as one unit. Bi-elemental lithotype components are xylo-detrite (xD) and detro-xylite (dX). When quantitatively estimated, these components are counted together with their surrounding fine-detrital matrix. A special 3 × 3 mm grid is used for quantitative estimations of the shares of separate lithotype components in percents. The grid is made on a PVC film fitting the borehole-core mantle.

In the past, during development of the classification, also somewhat different than the above cited terms were used (**Tab. 6.4**). They should be briefly explained here, because these can be encountered when looking at somewhat older documentation. The most continual designation was for xylite, which was for the whole time abbreviated by X (or XX and XXX, respectively). Fine detrite was frequently signed fD (fine detrite) or dD (from Slovenian “drobni detrit”). Xylitic pieces smaller than the core diameter were signed in the past as cD (coarse detrite) or gD (from Slovenian “grobni detrit”). At one time, a term Xylo-fragmentite (XFr.) was thought as an appropriate term for xylitic pieces smaller than the core diameter, but was abandoned soon.

Later, cD was replaced by XD (xylite-detritite), which was finally divided into dX (detritite-xylite – pieces smaller than half the core diameter), and xD (xylo-detritite – pieces bigger than half the core diameter but not exceeding it).

**Tab. 6.4:** Comparison between present and former abbreviations for constituent elements / lithotype components.

<b><i>Present abbreviations</i></b>	<b><i>Former abbreviations</i></b>	
	<b><i>In English</i></b>	<b><i>In Slovenian</i></b>
<b>D</b>	fD	dD
<b>xD</b>	cD; XD; XFr.	gD; XD
<b>dX</b>		
<b>dXxD</b>	XD	XD
<b>X, XX, XXX</b>	X, XX, XXX	X, XX, XXX

#### 6.3.1.2. Size limits of constituent elements of the lithotype components – Introduction of the UDEN scale into coal petrography

As lignite has an outstanding fragmental character of its composition and texture, an idea arose that the scale of UDEN (e.g. in SELLEY, 2000; TUCKER, 2001; and in many others) can be applied to define the size limits of the lignite-forming constituent elements.

The UDEN scale (supplemented with terms for fractions by WENTWORTH and transformed into the so-called Ø (phi) scale by KRUMBEIN in 1934) is very well known and the most widely accepted grain-size scale for clastic sediments and sedimentary rocks in the whole range of the following fractions: clay (<0.004 mm), silt (0.004–0.063 mm), sand (0.063–2 mm), granules (2–4 mm), pebbles (4–64 mm), cobbles (64–256 mm) and boulders (>256 mm). The UDEN scale is based on the function  $2^a$ , the exponent “a” being whole values from -8 to +12.

On the basis of the UDEN scale, the size criteria for constituent elements of the lithotype components can be adopted as shown in **Fig. 6.8**.

When studying lignite petrography in dimensions of borehole-core dimensions, the borehole-core diameter represents a practical orientation for further divisions of particle sizes of the lignite's plant derived constituent elements. The size value of **64 mm** was found to fit well to both, the value of the UDEN scale's function  $2^a$  and to a typical core diameter of (underground<sup>22</sup>) boreholes. As the next criterion, the lower limit at which, in praxis, the smallest xylitic particles are still visible and measurable had to be defined. This limit was decided to be at **1 mm**. For a

<sup>22</sup> Most of petrography was done on cores of underground.

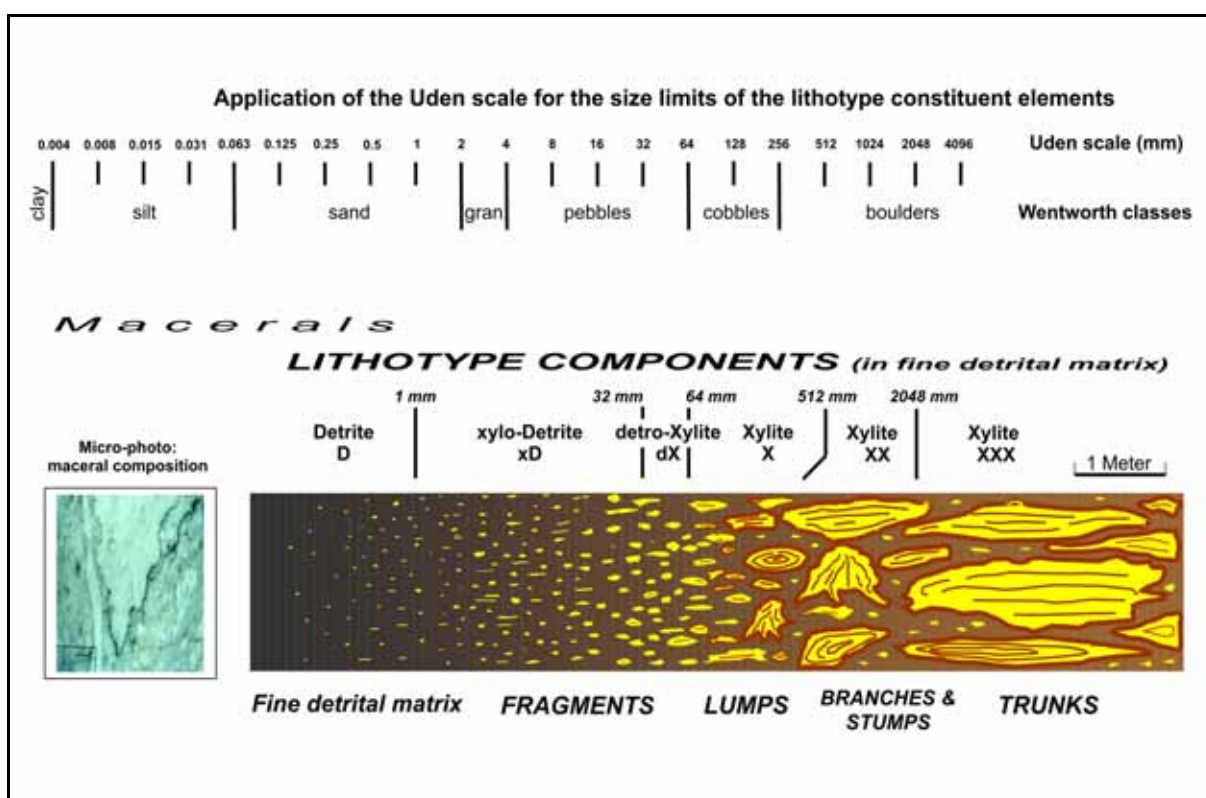
size limit between 1 and 64 mm, it was very reasonable to choose **32 mm**. Description of lithotype components as already given in **Chap. 6.3.1.1** can be thus supplemented with the following dimensional designations:

Plant material composed of particles below 1 mm in size forms the lithotype component, which is called **detrite (D)**.

Xylite pieces between 1 and 32 mm in size are constituent elements that form – together with the surrounding fine-detrital matrix – the lithotype component, which is called **xylo-detrite (xD)**.

Xylite pieces between 32 and 64 mm in size are constituent elements that form – together with the surrounding fine-detrital matrix – the lithotype component, which is called **detro-xylite (dX)**.

Fragments of wood exceeding 64 mm are termed **xylite (X)**.



**Fig. 6.8:** Application of the UDEN scale for the size limits of constituent elements that form lithotype components. (Macerals as microscopically recognizable constituents of coals are given only for relativity)

For observations in larger dimensions, such as in road-faces and long-walls (e.g. **Figs. 6.28, 6.29** and similar), two additional size limits for larger xylites were introduced at 512 mm (ca. 0.5 m) and at 2048 mm (ca. 2 m). For the largest wooden pieces it was not possible to find a name different from “xylite”, therefore these are termed as xylite **XX** and xylite **XXX**. They can be regarded as referring to tree branches, stumps and trunks.

### 6.3.1.3. Shape and orientation of the constituent elements

Regarding the shape and orientation of the lithotype-forming constituent elements, xylitic fragments are the most interesting. They may be of a very wide range of dimensions. If small, they are thinly flat or needle-shaped. Less than 1 mm thick fibrous xylitic enclosures termed as “lamellar xylite” are quantified together with detrite and marked by D(x). Larger xylitic pieces of XD (dXxD) and X size refer to fragments and lumps of bush and tree floral precursors. Still larger XX and XXX chunks are clearly attributed to big branches, stumps and trunks of tree vegetation. Larger elongated xylitic pieces are most often deposited parallel to the bedding, but their longer axes show different orientations on the bedding planes (on the paleodepositional surfaces). Xylitic fragments of XD sizes were observed to be distributed in the fine-detrital matrix either parallel to the bedding or chaotically. Quite often were encountered stumps, extending (semi)perpendicular to the bedding planes, up to 1 m high and 0.75 m wide, and usually deformed. Shape of xylitic fragments and pieces can have influence on adhesion between xylite and fine detrital matrix (see **Fig. 6.4**).

Both, the lack of a preferred orientation of xylites and the presence of stumps points out that the coal is of autochthonous origin.

### 6.3.1.4. Gelification

Gelification is the result of biochemical processes during the earliest stage of coal diagenesis (early coalification) up to the conversion of the vegetal matter into peat and soft brown coal (e.g., DIESSEL, 1992; and many others). It leads toward a structural homogeneity of coal. Gelified lignite is black, hard but brittle, with conchoidal fractures (**Fig. 6.9**). It typically exhibits a very pronounced cleat system<sup>23</sup> with average cleat spacing in the order of 0.5 to 2.0 cm. The cleats give to a gelified lignite its high permeability and specific geomechanical properties. Gelified lignite looks often as “the best quality coal” in a given setting.

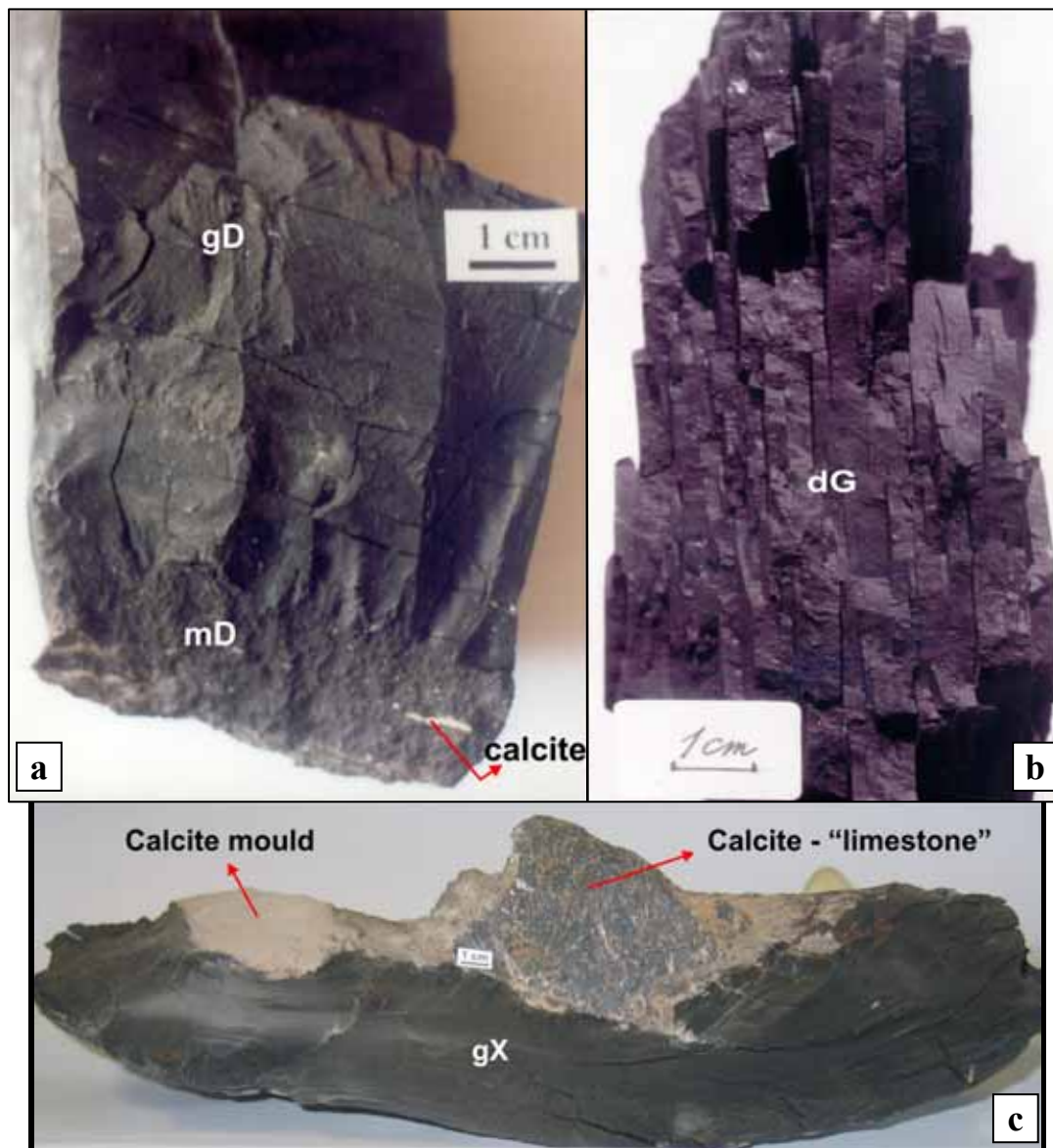
As commonly in lignites, also in the Velenje lignite gelification affected mostly its fine-detrital matrix. However, in the lower part of the seam, gelified wooden pieces may be encountered as well. This effect can be attributed to considerable groundwater influence, eutrophy and alkalinity<sup>24</sup> of the depositional milieu, which significantly enhanced bacterial activity.

As proposed in the ICCP lithotype classification (1993) (TAYLOR et al., 1998, p.280) (see **Tab. 6.1**), also the lithotype components of the Velenje lignite can be estimated as weakly gelified (**g**), or just as gelified (**G**) (**Fig. 6.9**). If the origin of the gelified matter is still recognizable, gelified

<sup>23</sup> Cleats are defined as vertical systematic extensional fractures in coals, which – in contrast to joints – do not cut clastic facies adjacent to coal layers (LAUBACH et al., 1998). Cleats are often confined to specific (micro-)lithotypes. Face cleats (dominant, probably formed first) and orthogonal butt cleats, which generally terminate when they encounter a face cleat, are distinguished (e.g. DAWSON & ESTERLE, 2010). Excellent papers about coal fracture systems, especially referring to studies about coalbed methane, have been e.g. written by PATTISON et al. (1996), FARAY et al. (1996), and GAMSON et al. (1996). In bituminous (or hard) coals, cleat density is the highest in bright coal (vitrain) layers, decreases toward banded coal (clarain) and is the lowest in dull coal (durain) layers. Gelified lignite resembles bright coal (vitrain). Therefore, cleat density in gelified lignite is typically high.

<sup>24</sup> As mentioned in **Chap 4.5**, alkalinity in peat-forming environments does not exceed pH of about 8.5. It is in fact weak alkalinity, but in relative terms of peat-forming environments, we often say that alkalinity of e.g. pH above 7.5 is already considerable.

components can be designated as **gelo-detritite (gD)** or **detro-gelite (dG)** if originating from fine-detrital matter, and as **gelo-xylite (gX)** and **xylite-gelite (xG)** if they are xylitic in origin, respectively. Because advancing gelification obscures the fragmental appearance of coal, strongly gelified lignite can be simply defined as “**gelite**” and signed by **G** solely.



**Fig. 6.9:** Gelified lithotype components of the Velenje lignite. **a)** **Gelo-detritite (gD)** with remarkable conchoidal fracture and some desiccation cracks overlying **mineral-rich detritite (mD)** with calcite inclusions as replacements of vegetal remnants. **b)** Typical **detro-gelite (dG)** with a notable cleat system developed close-to-perpendicular to the sub-horizontal bedding. **c)** Total replacement of the inner part of xylite (heart wood) by calcite – “limestone”. Xylite is gelified, termed as **gelo-xylite (gX)**. Pale (brown) mould on the gelo-xylite surface is also calcite.

As already pointed out above, a very pronounced cleat system is characteristic for gelified lignite. In non-gelified fine-detrital lignite or fine-detrital matrix, this system is less pronounced (see **Fig. 3.1-c,d** for the comparison), whereas it does not exist at all in (ductile) xylitic fragments, which are cut only by faults.



Fracturing of lignite was described in some more detail in footnotes <sup>23</sup> and <sup>24</sup> because it is one of the most obvious features when coal is observed from a relatively far distance. It reflects, although indirectly, petrographic composition, texture and structure of lignite. Fracturing pattern can be thus used as one of practical tools in lithotype distinction. However, attention must be paid during field work to distinguish natural and mining-induced fracture patterns. The latter can overprint the original one. This overprinting is not very welcome but the advantage is that also mining-induced effects are dependent on and reflect primary compositional, textural and structural characteristics of the lignite.

Whereas the degree of gelification can be macroscopically only estimated, it can be determined more precisely using micro-petrographic approaches, e.g. the so-called gelification index (DIESEL, 1986). Fine-detrital gelified matrix (gD–dG) is micro-petrographically exhibited as densinite, whereas gelified xylite (gX–xG) as texto-ulminite and eu-ulminite.

#### 6.3.1.5. Ratios between lithotype components – petrographic composition

Petrographic composition is evaluated by relative volume contents of the XXX, XX, X, F, dX, xD, and D lithotype components, by the contents of inorganic mineral admixtures and by the estimation of the gelification degree. XXX and XX components cannot be distinguished in the case of borehole-cores because they are too large in relation to borehole-core diameters. Fusite (F), which is quite a rare component, is mostly only signed as being present and its mode of occurrence is indicated.

Lithotype components in the whole range from D to XXX are fragmental constituents. They can be clearly evaluated in contents per area which approximate to the contents per volume. The latter, signed as vol. %, are therefore mostly used in the petrographic quantification. When composition is cited, the contents in vol. % are written after the abbreviations for the components. For example, composition written as dX15 – xD45 – D40 means that the lignite is composed of 15 vol. % of component dX, of 45 vol. % of component xD, and of 40 vol. % of component D.

Mineral matter in coal may be of different origins and forms (syngenetic, diagenetic or epigenetic, terrigenous or authigenic). It occurs laminated or layered, in concretions, dispersed within fine-detrital organic matrix, or in the form of replacements and encrustations of xylitic fragments. In spite of this heterogeneity, mineral matter content can be evaluated in most cases in vol. % with the exception of organic-inorganic complexes, which may not be recognized macroscopically. Beside clay admixtures, carbonate minerals are characteristic of the Velenje lignite.

Gelification cannot be expressed in vol. % but only ranked as cited in **Chap. 6.3.1.4**. However, for easier data management, gelification degrees are expressed in percentages as well. Weak gelification (g) is indicated by the values between 0 and 33 %, and pronounced gelification (G) by values between 33 and 66 %. For example, bulk composition XD20 – D64 – G16 (see e.g. borehole JV-768-H/98 at 180 m depth in **Fig. 6.26-a**) means that lignite is composed of 20 % of the XD component (containing xylitic pieces of the size between 1 and 64 mm), and of 80 % of fine-detrital matrix which is weakly gelified<sup>25</sup>.

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<sup>25</sup> 80 % fine-detrital matrix results from the sum of D64 and G16. 16 is 20 % (i.e. < 33 %) of 80, implying weak gelification.

One or more lithotype components form **lithotype varieties**. If borehole-cores are considered to be the basic dimensional framework, individual segments in the cores (**Figs. 6.25** and **6.26**) may be composed entirely of inorganic sediments (silt, sand, clay, marl etc.), entirely of lithotype component X, or entirely of lithotype component D. Such compositions are termed mono-component compositions. Considerably more frequent are bi- and poly-component lithotype varieties. Lithotype components being adjacent in the range  $X - dX - xD - D - dG$  are termed **“neighbouring”** components, while non-adjacent components are termed **“non-neighbouring”** components. For example, X and dX are the “neighbouring components”, while X and D are the “non-neighbouring” components.

In the following step of the discussion, the bi-component lithotype varieties will be treated as being composed of the “neighbouring” dX plus xD component and the D component. As already stated in **Chap. 6.3.1.1**, dX plus xD components can be uniformly called as the xylite-detritite XD or dXxD component. The question now arises how to define the ratios between the two components, the XD (or dXxD) and the D component. One solution, promoted in this monograph, is grouping of contents of the lithotype components into the following classes (expressed by vol. % of one of the components, either dXxD or D): <15; 15–40; 40–60; 60–85; 85–95; and >85 – as shown in **Fig. 6.10**.

The six dXxD – D classes are the slightly modified well accepted 0–10, 10–40, 40–60, 60–90 and 90–100 vol. % intervals for the description of “bright” (vitrain) to “dull” (durain) components of higher-rank coals “as in use in Australia” (DIESEL, 1965). In the case of brown coals, HONEK et al. (1999) proposed the same limits for the evaluation of detritic and xylitic components.

Bi-component lithotype varieties composed of the “non-neighbouring” components – e.g. of X and D – are encountered more rarely. If so, X layers should be thinner than 5 cm. If an X layer is thicker than 5 cm, it is treated as an individual component (see also **Fig. 6.6-a**). The 5 cm thickness criterion is applied because it fits reasonably to the 1:50 scale petrographic logging. This criterion is also similar to that used by TICLEANU et al. (1999) for the Pliocene lignites from Oltenia in Romania.

Further on, bi-component lithotype varieties may consist of one of the organic (phyto)lithotype components and of mineral admixtures. In such cases, the mineral component is always regarded as one of the non-neighbouring components.

Poly-component lithotype varieties are composed either of the “neighbouring” components (e.g. of X, XD and D (at X being thinner than 5 cm), or of the “non-neighbouring” components. It is logical that in coal-faces, where lithotype components are extended to XX and XXX components, more diversified compositions may be observed than in borehole-cores.

As inferred from the discussion so far, lithotypes of the Velenje lignite correspond to compositional classes as cited in **Fig. 6.10**. The question how to term lithotypes defined by the compositional intervals from **Fig. 6.10** was of low-priority. In a vast petrographic documentation prepared for the VLM during the last 15 years, the petrographic composition of lignite observed in cores, road-faces, long-walls etc. was expressed in terms of lithotype components, and – more uniformly and practically for computer data management – by code values. The codification system will be presented in the following chapter, but prior to that, a few words may be dedicated to more “colloquial” lithotype designations as well.



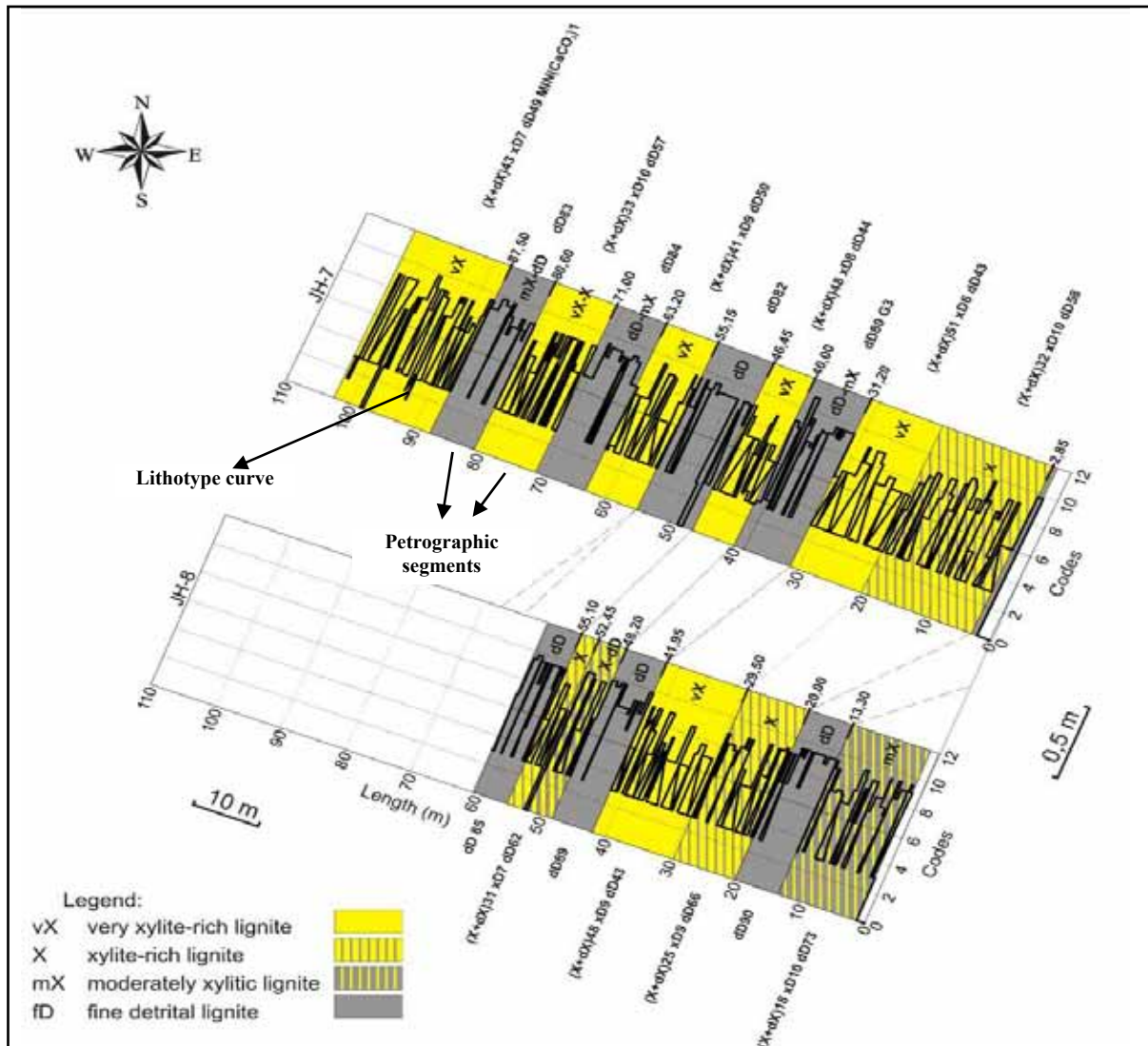
MACROPETROGRAPHIC PATTERN Core diameter 63 mm	LITHOTYPE COMPONENTS (classes in vol. %)	CODE textural	
	Sand and silt	1	1.5 (w)
	Clay	2	
	Mineral-rich lignite	combination	
	X	3 (w)	
	X and dX	3.5 (w)	
	dXxD > 85 D < 15	4 (w)	
	dXxD 60-85 D 15-40	5	5.5
	dXxD 40-60 D 40-60	6	6.5
	dXxD 15-40 D 60-85	7	7.5
	dXxD 5-15 D 85-95	8	9
	D > 95	9.5 (w)	
	Gelification - weak g	10	
	Gelification - pronounced G	15 (w)	

**Fig. 6.10:** Schematic presentation of lithotype components (graphics on the left), classes of lithotype composition (in the middle), and “textural” code values for specific compositional classes (on the right). Note that dXxD means the sum of dX and xD components and that the two code values for the same content class (e.g. 6 and 6.5) designate the prevalence of one of the lithotype components (the lower code 6 implies the predominance of the dX component, whereas the higher code 6.5 implies the predominance of the xD component). Abbreviation “w” means “weight code” value. This classification is especially usable in borehole-core petrography and hand specimens – note a schematic scale of 63 mm on the top left. More about codes and codification procedure is written in *Chap. 6.3.1.8*.

Among “colloquial” lithotype terms, the term “**fine-detrital lignite**” is one of the clearest one, because this type of lignite is typically homogeneous. Fine-detrital lignite designates the lignite which involves less than 15 vol. % of the dXxD lithotype component – with xD prevailing over dX (see **Fig. 6.10**). Lignite containing 15–40 vol. % of xylitic inclusions of sizes xD to XXX is called **xylite-rich lignite**, and that, which contains more than 40 vol. % of various xylitic fragments is called **very xylite-rich lignite**. Other lithotype terms, such as

**charcoal (fusite)-rich lignite** and **mineral-rich lignite** are used more or less in the same sense as in **Tab. 6.1** after the ICCP (1993)<sup>26</sup>.

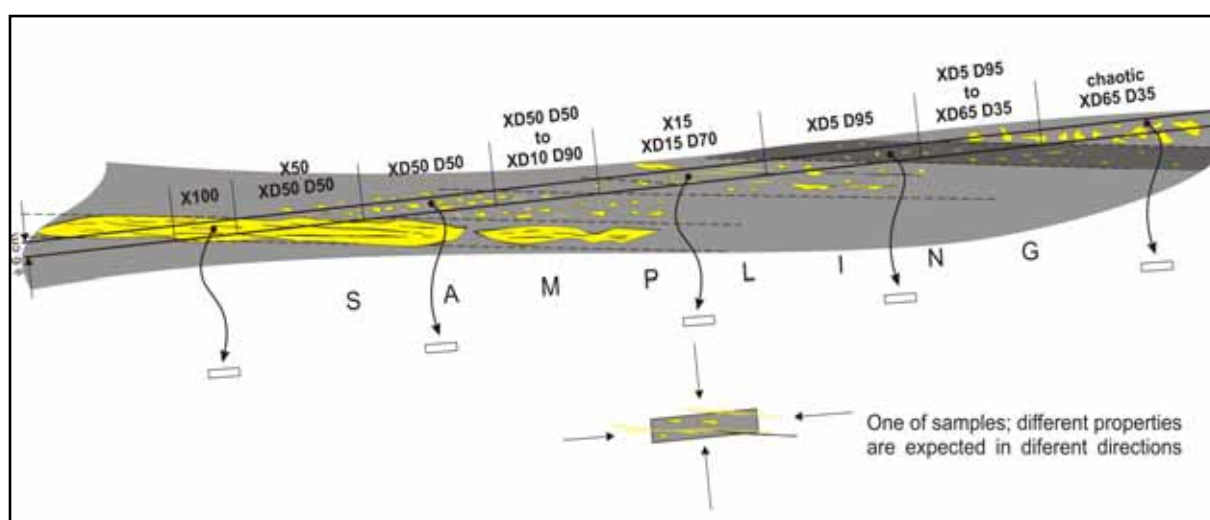
A graphical example, showing the use of a variety of lithotype designations (codification, lithotype components by vol. %, and “colloquial” lithotype expressions), is displayed in **Fig. 6.11**. More examples are dealt with in **Chap. 6.3.2**.



**Fig. 6.11:** Correlation of lithotype (facies) segments between two boreholes drilled almost horizontally at a low angle in relation to the lignite-seam bedding (see **Fig. 6.19**). Source petrographic logging was documented in detail as shown in **Fig. 6.6**. In this figure, petrography is expressed: 1) by code values versus depth – i.e. by a lithotype curve, 2) by composition in terms of contents of lithotype components in the interpreted petrographic segments, and 3) by “colloquial” terms (see legend) for the different segments.

<sup>26</sup> As discussed in **Chap. 6.1** and **Tab. 6.2**, also brown-coal (lignite) lithotypes could have a characteristic ending “ain”, so to be termed as xylain, detro-xylain, detrain, fusain, minerain, but, in reality, such terminology did not (yet) find a formal usage.

When speaking about coal petrographic data and results it is common to speak in terms of lithotype, maceral and/or microlithotype composition, rather than in terms of **facies** and **microfacies**. It is not the space here to go deeply into clarifying the reasons why this is so, it is sufficient to borrow a sentence from GARY et al. (1972) (in TAYLOR et al., 1998, p.26) defining facies in the following way: “Facies is the sum of all primary lithologic and paleontologic characteristics exhibited by a sedimentary rock and from which its origin and formation may be inferred”. In the case of the Velenje lignite, we mainly use the term “facies” when describing petrographically distinct units or segments within the lignite seam. **Fig. 6.11** provides an illustrative example, in which distinguishable coal facies segments can be termed as fine-detrital lignite facies, xylite-rich facies, mineral-rich lignite facies, etc. (for segmentation see also **Fig. 6.26**). Mostly such segments as interpreted from boreholes represent coal layers or bed-sets as schematically shown in **Fig. 6.12**.

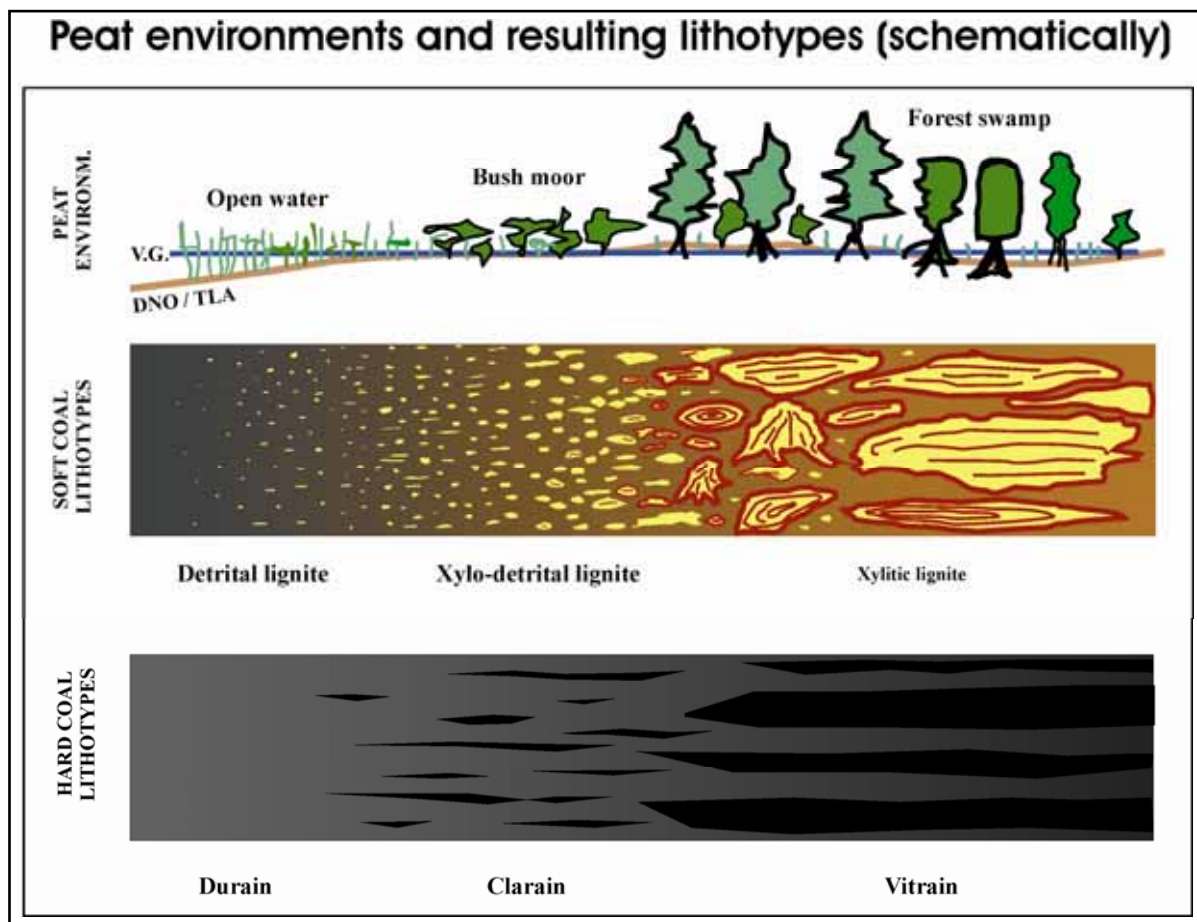


**Fig. 6.12:** Schematic presentation of the lignite facies variations along a nearly horizontal borehole cutting the lignite layering at a low angle. The sketch was made on the occasion of sampling for petrophysical measurements in 1999. The orientation of coring and subsequent sampling is crucial in determining different rock-mechanical and petrophysical characteristics of lignite.

### 6.3.1.6. Lithotype classification and interpretation of peat-forming environments

An important aspect of sedimentary petrographical classifications in general (as e.g. discussed by SKABERNE, 1980) is that they are as good as they carry not only information about the composition and texture but also useful information about rock genesis. Among physical parameters that define a rock, especially those having a significant genetic meaning should be taken into consideration. Grain size of sediments/sedimentary rocks and more or less closely related composition are therefore considered as the most important classification elements. In clastic rocks grain size distribution is highly dependent on the energy level of the transport medium. As e.g. said by REINECK & SINGH (1980, p.132) “The grain size of a clastic sediment is a measure of the energy of the depositing medium and the energy of the basin of deposition”. In the case of coals, the “grains” are formed to the greatest part from the autochthonous, in-situ growing vegetation, which, after dying and before settling down, does not surpass any transport-related energy separation. Thus, it is only the original vegetation distribution that plays a decisive role in the final lithofacies variability of a coal observed. Apart from external factors, such as

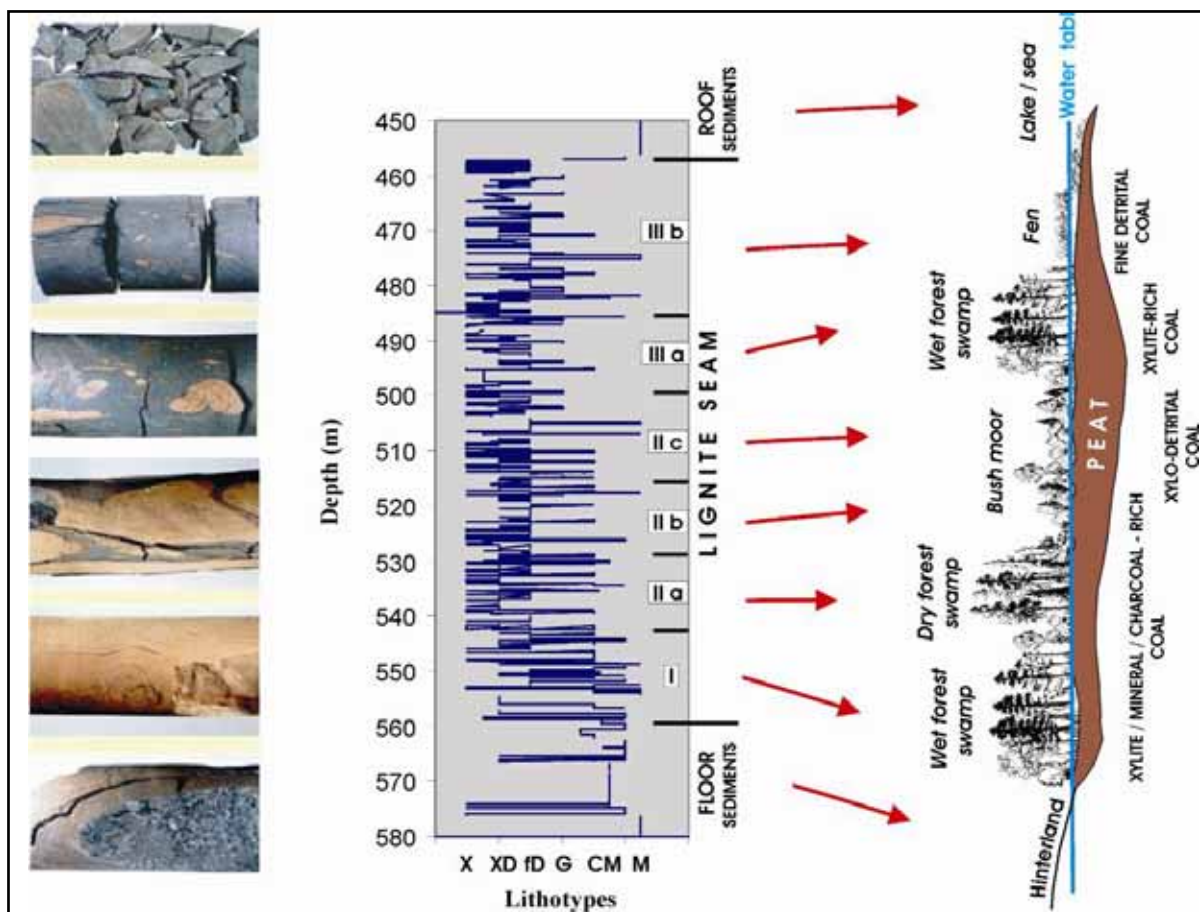
climate and the availability of soils and seeds, in principle, vegetation distribution is highly susceptible to the height of the (ground)water table. Forest swamps and bush moors, either “dry” or “wet”, moss bogs, grasslands and fens of open-water surfaces are the most important peat-forming environments. A simple cartoon showing the relation between lithotype composition and peat-forming environments is shown in **Fig. 6.13** (extended also to lithotypes of hard coals).



**Fig. 6.13:** Peat-forming plants and environments as pre-coursing factors in the formation of different lithotypes of soft coals (lignites) and hard coals (schematically).

In the case of Velenje, more precisely in the case of the petrographic analysis of borehole P-9k/92, which will be discussed in detail in **Chap 6.4**), an illustration of the interpreted peat-forming environments and adequate lithotype characteristics is given in **Fig. 6.14**.





**Fig. 6.14:** Characteristic lithotypes of the Velenje lignite (taken from Figs. 6.3 and 6.5), lithotype log of lignite from borehole P-9k/92, petrography-based segmentation of the profile into units I to IIIb (from MARKIČ & SACHSENHOFER, 1997), and reference to the peat-forming environments as illustrated in a classical work of TEICHMÜLLER (1958). (See also Chap. 6.4.1.4.4). Note that the interpretation is based not only on macro-petrographic data, but also considers micro-petrography, ash yield, sulphur contents, floor and roof rocks.

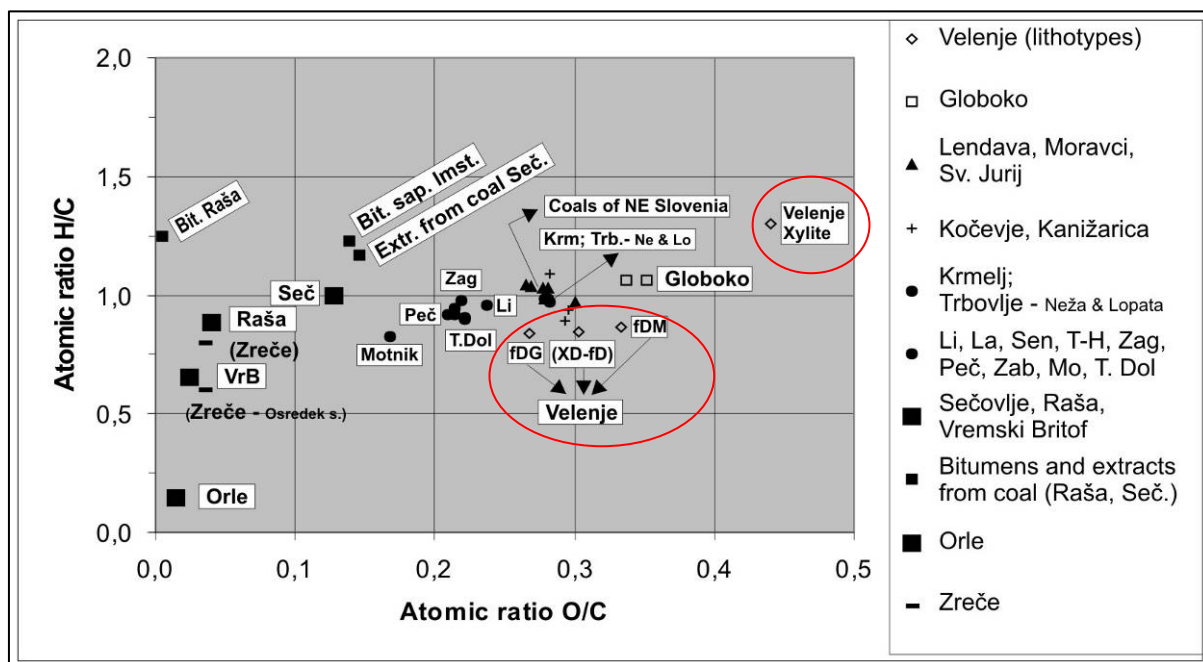
### 6.3.1.7. Elemental and isotopic composition of macro-lithotypes

Elemental composition of different lithotypes of the Velenje lignite was studied in 1998 by S. HOČEVAR from the Chemical Institute in Ljubljana (reference “a” in Tab. 6.5). Results of this study and recalculations to elemental atomic ratios were summarized in MARKIČ et al. (2007), who compared H/C versus O/C atomic ratios of selected coals in Slovenia (Fig. 6.15).

Among the Velenje lithotypes, xylite has the lowest carbon (57.8 %  $C_{totdaf}$ ) and the highest hydrogen (6.3 %  $daf$ ) contents. Moreover it is characterized by the highest H/C and O/C ratios (Fig. 6.15). Apart from showing the low rank of the Velenje coal (see Chap. 7), high H/C and O/C ratios reflect relatively high contents in cellulose and lignin in the fossil wood. The mean carbon content in xylo-detrital and fine-detrital (XD-fD) petrographic varieties of lignite is 65.0 %  $C_{totdaf}$ , whereas it is even 67 %  $C_{totdaf}$  in gelified fine-detrital lignite (GfD-fDG).

**Tab. 6.5:** Mean elemental composition, H/C and O/C atomic ratios, coal quality, and rank by GCV<sub>daf</sub> for different lithotypes of the Velenje lignite. Abbreviations for the lithotypes are as follows: X – xylite; XD-fD – xylo-detrital to fine-detrital lignite; GfD – gelified fine-detrital lignite; fDG – strongly gelified fine-detrital lignite or “gelite”; MfD, fDM – mineral-rich fine-detrital lignite, fine-detrital minerite. Abbreviations for coal quality and rank parameters are: M – moisture; A – ash; OM – organic matter; NCV – net calorific value; GCV – gross calorific value. The bases are: daf – dry, ash-free; db – dry; ar – as received. (Adopted from MARKIČ et al., 2007).

Velenje lignite lithotypes	Reference N° of samples	Elemental composition					Atomic ratios		Coal quality					Rank	
		C	H	O	N	O+N	H/C	O/C	S <sub>tot</sub>	M	A	OM	NCV	NCV	GCV
		mass %							mass %					MJ/kg	MJ/kg
		daf basis							db					daf	
X	1	57.8	6.3	33.9	0.4	34.3	1.299	0.440	1.61	10.30	6.50	83.20			
XD-fD	2	65.0	4.6	26.2	2.2	28.4	0.843	0.303	1.85	20.35	7.40	72.25			
GfD, fDG	3	67.0	4.7	23.9	2.1	26.0	0.836	0.268	2.06	21.47	9.30	69.23			
MfD, fDM	2	63.6	4.6	28.2	1.9	30.1	0.862	0.333	1.31	14.50	24.90	60.60			
X	5									17.02	4.83	78.15	17.475	22.36	24.05
XD-fD	11									15.19	8.16	76.65	18.432	24.05	25.69
XD-fD	8									15.76	6.33	77.91	19.107	24.52	26.14
GfD-fDG	20									15.13	6.12	78.75	19.590	24.88	26.42



**Fig. 6.15:** Characterization of selected coals in Slovenia, including the Velenje lignite, by H/C versus O/C atomic ratios (Van Krevelen's diagram) – for locations of the coals, see Fig. 2.1. For lithotype abbreviations of the Velenje lignite see explanation in Tab. 6.5. (From MARKIČ et al., 2007).

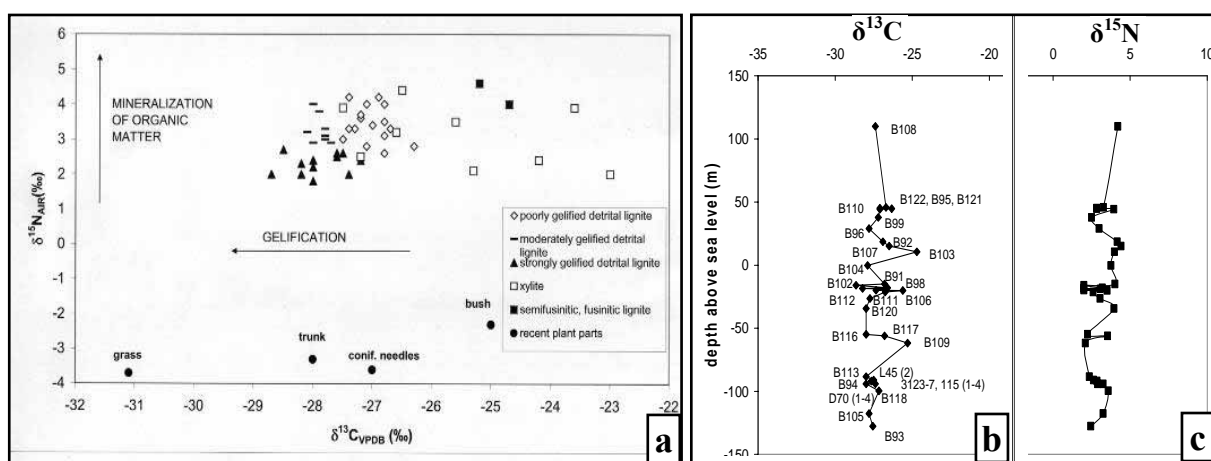
It is interesting to note that the detrital Velenje lignite lithotypes exhibit lower H/C ratios than coals of approximately the same coal rank (samples with similar O/C ratios; Fig. 6.15). This fact reflects low proportions of hydrogen-rich macerals (liptinite) in detrital lithotypes and indicates subtle oxidation of the Velenje lignite. Fusinitization and semidegradofusinitization due to bacterial and fungal activity (as observed microscopically), sporadic siderite mineralization, as well as exposure of individual xylite pieces above the peat surface and their erratic calcification may be explained in this way. A further interesting fact is the relative enrichment of O (high O/C ratio) in fine-detrital mineral-rich lignite (fDM) in comparison to



fine-detrital gelified lignite, which is characterized by the lowest O/C ratio among the Velenje lignite lithotypes in **Fig. 6.15**. In the case of fDM, the detrital mineral influx is an indicator of an oxygenated peat-water environment, whereas in the other extreme, in the case of fDG, peat-water milieu was calm, eutrophic, more alkaline, and more suitable for bacterial activity during peatification.

Whereas hydrogen and oxygen contents reach a maximum in xylite, nitrogen contents are higher in detritic coal varieties. Incorporation of bacterial biomass (rich in nitrogen) may be responsible for the relatively high nitrogen contents. Because both, gelification and sulphur reduction are controlled by bacterial activity, it is not surprising that the gelified lithotypes contain the highest percentage of sulphur (2.1 %).

Differences in elemental composition of lithotypes are also reflected by the isotopic composition of carbon and nitrogen. KANDUČ et al. (2005) investigated the isotopic composition of carbon and nitrogen using samples of different lithotypes taken from different locations within the underground mine. The following lithotypes have been studied: poorly, moderately and strongly gelified detrital lignite, xylitic pieces, and charcoal-rich lignite<sup>27</sup>. This study revealed that the bacterially governed process of gelification causes isotopic fractionation of carbon ( $\delta^{13}\text{C}$ ) and that the mineralization process causes isotopic fractionation of nitrogen ( $\delta^{15}\text{N}$ ) (**Fig. 6.16-a**). The latter process (enrichment in mineral matter as a residue



**Fig. 6.16:** a)  $\delta^{13}\text{C}_{\text{VPDB}}$  versus  $\delta^{15}\text{N}_{\text{AIR}}$  of different lithotypes of lignite from the Velenje basin. Decreasing  $\delta^{13}\text{C}$  values indicate the process of gelification. Increasing  $\delta^{15}\text{N}$  values indicate the process of mineralization of organic matter. b) and c)  $\delta^{13}\text{C}_{\text{VPDB}}$  and  $\delta^{15}\text{N}_{\text{AIR}}$  values of lignite versus depth (relative to sea level). (From KANDUČ et al., 2005).

due to the loss of organic matter because of oxidation) is interesting since it is a tight reflection of oxidation, which causes e.g. the formation of inertinitic components. Indeed, char-coalified (semifuinitic and fusinitic in **Fig. 6.16-a**) samples showed the most positive

<sup>27</sup> In working nomenclature (as e.g. cited in legend **Fig. 6.16**, borehole logs in Figs. ...., etc.), charcoal-rich (or fusitic) lignite was often called as fusinite (and/or semifuinitic)-rich lignite. Fusinite and semifuinitic are terms for microscopically distinguishable macerals of coal, and should not be used for macro-petrographic description. However, charcoal is almost undoubtedly identified under microscope as fusinite (and/or semifuinitic), and this is the reason why the term “fusinitic” coal, or “fusinite” for char-coal particles is often (wrongly) used also in cases of macro-petrography.

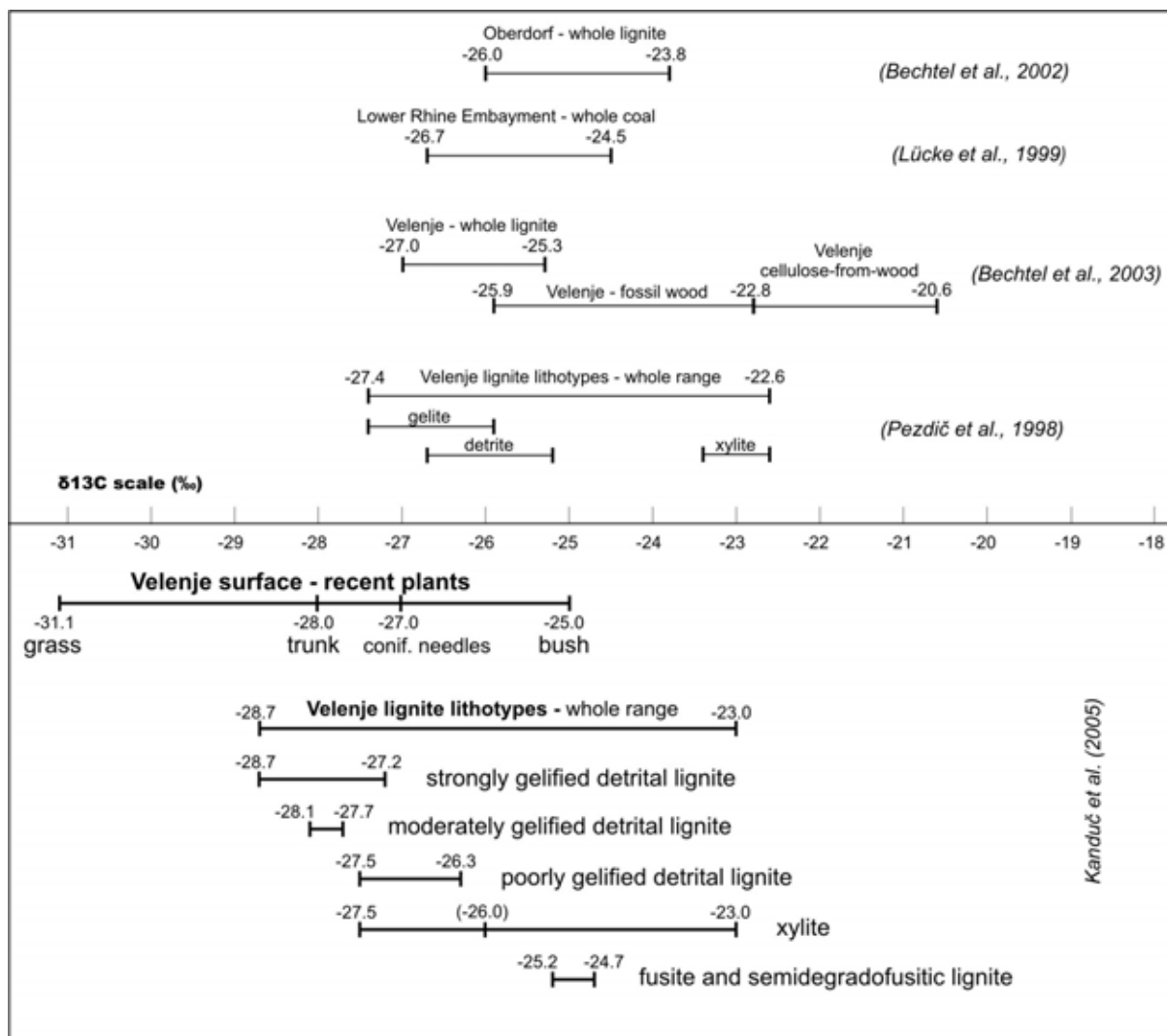
$\delta^{15}\text{N}$  values, which are characteristic for highly mineralised organic matter, whereas strongly gelified samples revealed the most negative values of this isotope.

$\delta^{13}\text{C}$  values are more discriminant than  $\delta^{15}\text{N}$  values. The most negative  $\delta^{13}\text{C}$  values (-28.7 to -27.2 ‰) are characteristic for strongly gelified detrital lignite, whereas a wide range of values (-27.5 to -23.0 ‰) is characteristic for xylites (KANDUČ et al., 2005). For the Velenje lignite, a similar relation, i.e. depletion of  $^{13}\text{C}$  (more negative  $\delta^{13}\text{C}$  values) in “whole coal” (fine detrital matrix coal) in comparison to xylite was detected (PEZDIČ et al., 1998; BECHTEL et al., 2003). Moreover, in a biomarker and carbon isotope study of Cenozoic low-rank coals from Central Europe, BECHTEL et al. (2008) confirmed that depletion of  $^{13}\text{C}$  in “whole coals” in comparison to xylites is a general feature of investigated late Oligocene to Pliocene coals, if xylite is derived from gymnosperm wood. If the fossil wood is derived from angiosperms, such xylites have similar carbon isotopic composition as “whole coals” (BECHTEL et al., 2008, their Fig. 7).

From the isotopic characteristics of the Velenje lignite lithotypes it can be concluded that samples of strongly gelified detrital lignite characterized by a narrow range of C and N isotopic compositions indicate uniformity in both the gelification and the mineralization processes (**Fig. 6.16-a**). This can be explained in a way that original organic material was homogeneous and was transformed in uniform eH reducing environment(s). On the other hand, a wide range of N and C isotope values for xylites implies that xylites were affected in a wider spectrum of environmental conditions, from anaerobic (reducing) to aerobic, and were differently affected by biochemical processes. The speculation about anaerobism versus aerobism on the basis of C isotopic composition is in a good agreement with e.g. cellulose yield data (BECHTEL et al., 2003), which also showed that xylites could be exposed to either more or less intensive activity of aerobic and anaerobic bacterial activity, respectively.

In the study of KANDUČ et al. (2005) it was revealed that the isotopic composition of carbon and nitrogen is dependent on lithotype, but not on sampling depth (**Fig. 6.16-b**). Only N shows a vague upward-increasing trend in positivity of  $\delta^{15}\text{N}$  values (**Fig. 6.16-c**). Because N and C isotopic composition is not depth- (time-) dependant but depends almost exclusively on lithotype and maceral composition, it can be supposed that the processes of humification, gelification and mineralization were temporally and spatially very similar and uniformly intensive during peat and lignite formation.

A comparative overview of results of carbon isotopic investigations of the Velenje lignite and two other well studied coals (Oberdorf, Austria; Lower Rhine Embayment; Germany) is given in **Fig. 6.17**. For more information about isotopic composition of coals in Central Europe and its controlling processes, the reader is referred to the already mentioned paper of BECHTEL et al. (2008).

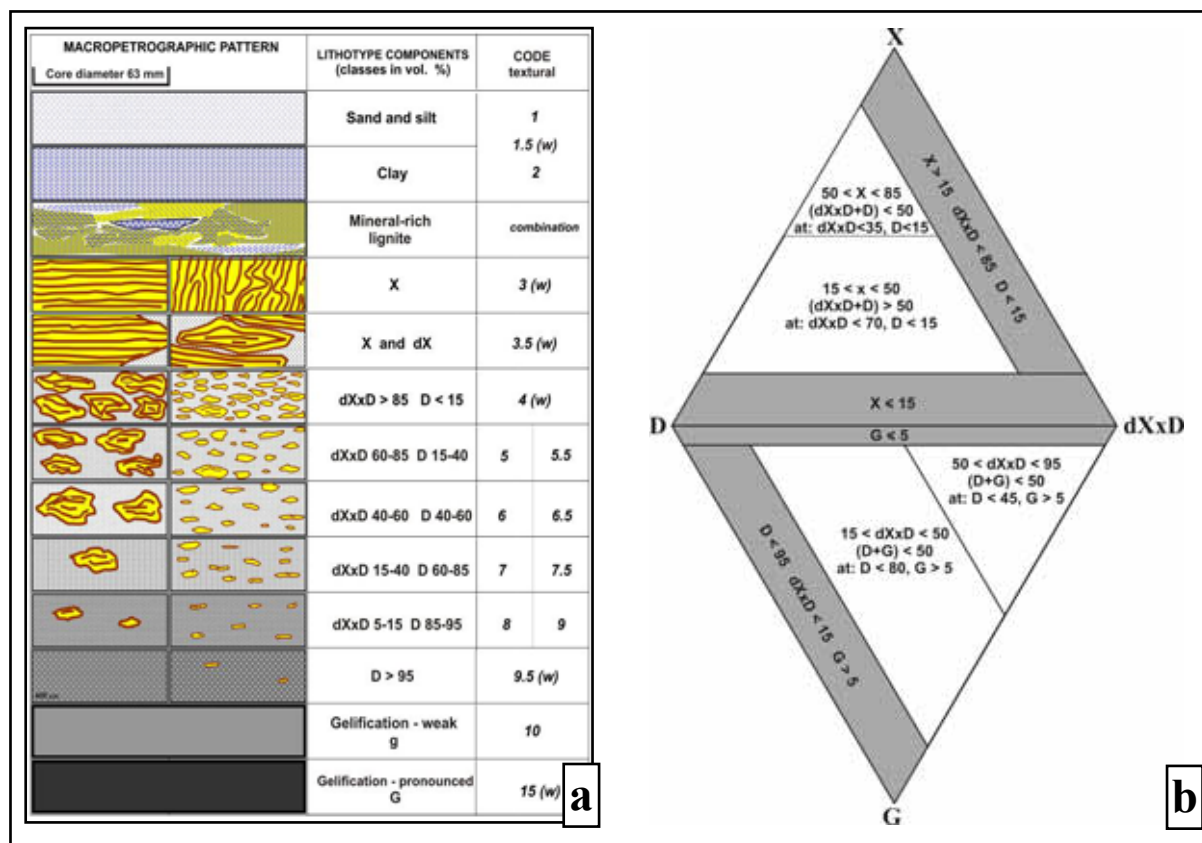


**Fig. 6.17:** Comparison of  $\delta^{13}\text{C}$  values from the Pliocene Velenje lignite (based on data from PEZDIČ et al., 1998, BECHTEL et al., 2003; and KANDUČ et al., 2005), the Miocene Lower Rhine Embayment brown coal (LÜCKE et al., 1999), and the Miocene Oberdorf lignite (BECHTEL et al., 2002) (From KANDUČ et al., 2005).

### 6.3.1.8. Codification of petrographic composition of lignite in borehole-cores

The codification system to express the petrographic composition of lignite was developed in order to simplify the description of petrographic composition and structure of lignite and to ease data management. It is used in the petrography of borehole-cores and hand-specimens<sup>28</sup>. It is especially suitable for the presentation of whole borehole-core logs in different scales (Figs. 6.25 and 6.26). Codification was already included in Fig. 6.10. Here, it will be discussed more in detail (Fig. 6.18).

<sup>28</sup> Underground road-faces and long-walls provide large surfaces of lignite, which allow a clear delineation of large-scale petrographic units. However, because of poor working conditions in the active mine, lithotype characterization is generally less accurate. Thus, codification was not applied for mapping of mine workings.



**Fig. 6.18: a)** Basic system of lithotype codification (see also Fig. 6.10). Source (textural) code values are cited. Two code values for the same content class (e.g. 6 and 6.5) designate the prevalence of one of the lithotype components (the lower code 6 implies the predominance of dX, whereas the higher code 6.5 implies the predominance of the xD component). Code values signed by “w” mean “weight code values”. **b)** Double three-component  $X - dXxD - D$ , and  $dXxD - D - G$  diagram. Compositions within grey fields are coded by **calculated codes**, while compositions within white fields are coded by **combined codes** (see more explanation in the text).

The codification concept (Fig. 6.18-a) is primarily based on:

- codification of mono-component lithotype varieties,
- codification of bi-component lithotype varieties composed of the “neighbouring” dXxD and D components, and
- codification of the intensity of gelification

Such systems are codified by the so called **source codes** (or **textural codes**) which have the numerical form of a whole number (e.g. 3) or of a number with one decimal place at .5 (e.g. 5.5, 6.5 etc.) (Fig. 6.18-a).

Other compositions, which consist either of “non-neighbouring” components or of more components, are expressed either by different combinations of the source codes, which are termed **combined codes**, or by the so called **calculated codes**. The latter are calculated by using **weight code values** (see Equation 6.1). They are numerically expressed in the form of two-decimal numbers (e.g. 3.14, 5.57, 6.50 etc.). The whole range of codification in all cases is from 1 to 15.

Like in the case of other sedimentary petrographic systems, also the composition of coals can be presented by triangle diagrams. An approach in this sense is given in **Fig. 6.18-b**. In the triangles, modes of codification are cited. Compositions, which can be expressed by the **source codes**, fall on the outer lines of the triangles. Compositions within grey fields are coded by **calculated codes**, while compositions within white fields are coded by **combined codes**.

#### 6.3.1.8.1. Codification by source codes and weight code values

Mono-component lithotype varieties, compositions of the bi-component varieties being composed of the “neighbouring” dXxD and D components, and the two stages of gelification are expressed by source codes from 1 to 15 as presented in **Fig. 6.18-a**.

Source codes 1 and 2 mean inorganic sediments, mostly termed as mineral admixtures (Min. adm.).

The codification of “true lignite” starts with code values 3 and 3.5 for xylite (X) and detro-xylite (dX), respectively. These are followed by codes 4, 5 and 5.5, 6 and 6.5, 7 and 7.5, 8 and 9, and 9.5 for the six dXxD – D classes. Two code values for the same content class (e.g. 5 and 5.5, 6 and 6.5, ..., up to 8 and 9) designate the prevalence of one of the lithotype components within the dXxD component. If larger xylitic fragments (dX) prevail over the smaller (xD), than the code value is slightly lower (e.g. 6 instead of 6.5), and vice versa.

Codes 10 and 15 express the two degrees of gelification that mostly refer to the gelified fine-detrital matrix.

Codes 1.5 (Min. adm.), 3 and 3.5 (entirely X and X plus dX), 4 (dXxD>85 – D<15), 9.5 (D>95) and 15 (G) are termed the **weight code values**.

It can be observed that differences between the source codes (**Fig. 6.18-a**) are not strictly constant. They are most often 0.5 (e.g. between codes 9 and 9.5), 1 (e.g. between codes 8 and 9), and even 5 (between the degrees of gelification). These differences point out the contrasts in regard to lignite appearance and exhibit some genetic aspects as well. For instance, a dXxD>85 – D<15 lithotype variety (code 4) is structurally (and genetically!) closer to the entirely xylitic X100 variety (code 3) than to the dXxD(60-85) – D(15-40) variety (code 5.5).

#### 6.3.1.8.2. Codification of bi-component lithotype varieties composed of non-neighbouring components by combined codes and by calculated codes

Lithotype varieties composed of two non-neighbouring components – i.e. of relatively contrasting components – are codified either by a combination of two weight code values for each of the components or by the calculated codes.

The combined coding is used when each of the components exceeds 15 vol. %. The first code value always describes the component that exceeds 50 vol. %. If a lithotype variety is composed of one component equal to or lower than 15 vol. %, it is better to apply calculated coding.

Examples of the two different modes of codification are given below (combined coding in **Tab. 6.6** and **6.7**, and calculated coding in **Tab. 6.8**).

**Tab. 6.6:** Combined coding for bi-component lithotype varieties composed of non-neighbouring components.

Composition	Code (comb.)
X(15-50) – D(50-85)	9.5/3
X(50-85) – D(15-50)	3/9.5
Min.adm in D(15-50) – D(50-85)	9.5/1.5
Min. adm. in D(50-85) – D(15-50)	1.5/9.5
Min. adm. in X (15-50) – X (50-85)	3/1.5
Min. adm. in X (50-85) – X (15-50)	1.5/3
etc.	

**Tab. 6.7:** Codification of gelified xylite. The gelification of xylite is regarded as more extraordinary than the gelification of fine-detrital matrix. The gelification of xylite is therefore considered as a quite “contrasted” phenomenon. Intermediate degrees of gelified xylite may be signed as 10/3 and 3/15, respectively, but these are more theoretical examples.

Composition	Code (comb.)
Weakly gelified xylite (gX)	3/10
Strongly gelified xylite (xG)	15/3

Calculated coding is carried out by considering the contents of the individual components in vol. % and their characteristic weight code values. Calculated codes (CC) are obtained by the following equation (**Eq. 6.1**):

$$CC = \frac{1}{100} \times [(1.5 \times a) + (3 \times b) + (3.5 \times c) + (4 \times d) + (9.5 \times e) + (15 \times f)] \quad (\text{Eq. 6.1})$$

where abbreviations *a* to *e* are the contents (in vol.%) of the mineral admixtures (*a*), X (*b*), X plus dX (*c*), dXxD (*d*) and D (*e*), and *f* is a numerical expression of the gelification degree. Values 1.5, 3, 3.5, 4, 9.5 and 15 are the weight codes for the cited components. Calculated coding is presented in **Tab. 6.8**:



**Tab. 6.8:** Calculated coding for bi-component lithotype varieties composed of non-neighbouring components. Note that in all cases one of the components is below 15 %, and the other one is above 85 %.

Composition	Calculation	Code (calculated)
X10 – D90	$\frac{1}{100} * [(3 * 10) + (9.5 * 90)] = 8.85$	<b>8.85</b>
X95 – D5	$\frac{1}{100} * [(3 * 95) + (9.5 * 5)] = 3.33$	<b>3.33</b>
Min.adm. (in D)15 – D85	$\frac{1}{100} * [(1.5 * 15) + (9.5 * 85)] = 8.30$	<b>8.30</b>
Min. adm. (in D)95 – D5	$\frac{1}{100} * [(1.5 * 95) + (9.5 * 5)] = 1.90$	<b>1.90</b>

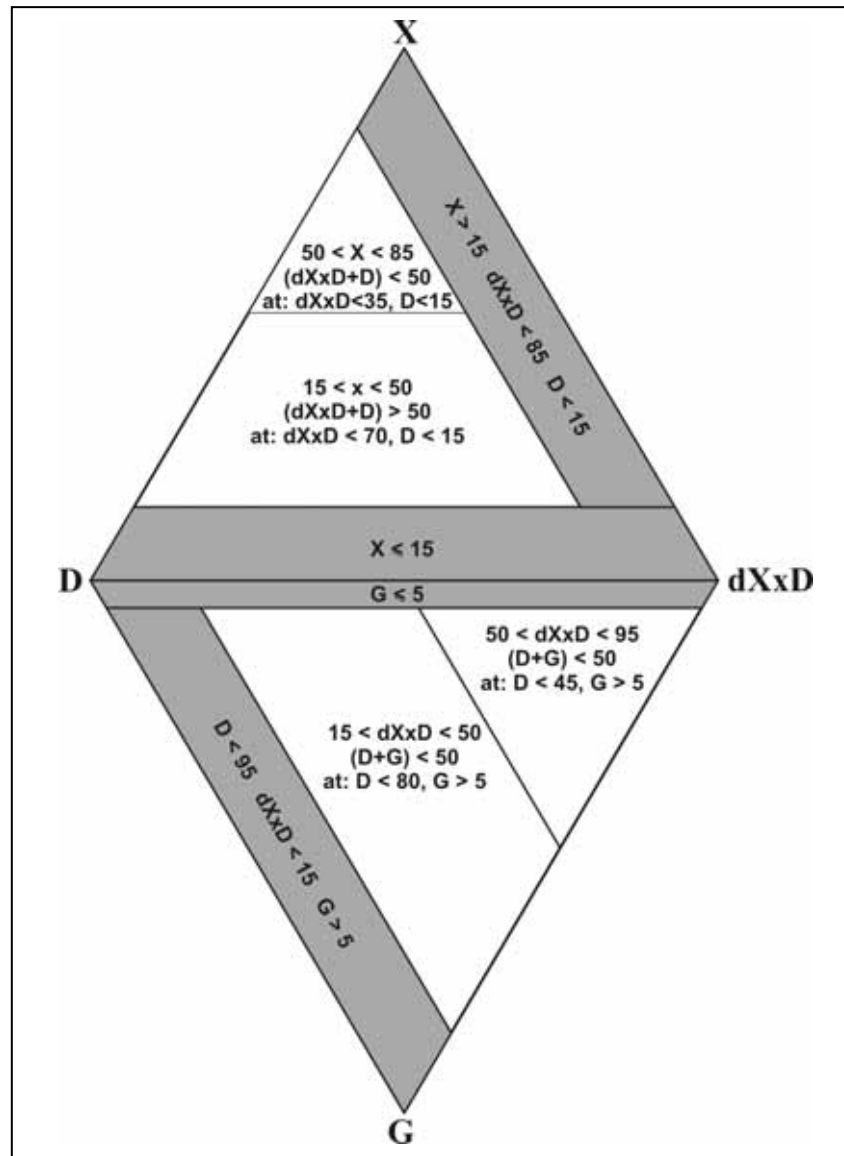
#### 6.3.1.8.3. Codification of poly-component lithotype varieties

Codification of the poly-component lithotype varieties follows similar rules as for the bi-component varieties.

Relatively heterogeneous compositions are expressed by combined codes if each of the X, dXxD and D components exceeds 15 vol. %, and/or gelification G is noted (registered as >5%). For more uniform lithotype varieties (X or dXxD or D ≤ 15 vol. % and/or G ≤ 5 %), calculated coding is used. Criteria for both modes of codification are quantitatively presented in the double three-component diagram X – dXxD – D and dXxD – D – G in **Fig. 6.18-b**. For easier insight, the double three-component diagram is shown in **Fig. 6.19** once again. Grey fields in **Fig. 6.19** represent compositions coded by the calculated codes, whereas white fields represent compositions coded by the combined codes.

In the case of heterogeneous X – dXxD – D compositions, one code value is attributed to the dXxD – D ratio because this ratio can be expressed by the source coding (**Fig. 6.18-a**) if recalculated to 100 %, and another code value is attributed to the X component. Similarly, in the case of heterogeneous dXxD – D – G compositions, one code value is attributed to the D – G ratio and another one to the dXxD component. Some examples are given in **Tab. 6.9**.

In the case of the uppermost X30 – dXxD30 – D40 composition in **Tab. 6.9**, the ratio dXxD30 – D40 is transformed into the ratio dXxD43 – D57 if recalculated to 100 %, and therefore it is coded by source code 6.5 (if xD prevails over dX – see **Fig. 6.18-a**). Source code 3 for X is cited because the content of X is above 15 vol. %. When X content exceeds 50 % (second example in **Tab. 6.9**), source code 3 for X is cited first. Combined codes for the dXxD – D – dG compositions are obtained in a similar way.



**Fig. 6.19:** Double three-component  $X - dXxD - D$  and  $D - dXxD - G$  diagram (same as in **Fig.6.18-b**). Compositions within grey fields are coded by **calculated codes**, while compositions within white fields are coded by **combined codes** (see more explanation in the text). Note that  $X$  and  $G$  are shown as the most apart “end-members” as they are also genetically the most contrasted components.

**Tab. 6.9:** Combined coding for heterogeneous poly-component  $X - dXxD - D$  and  $dXxD - D - G$  compositions.

Composition	Code (comb.)
X30 - dXxD30 - D40	6.5/3
X65 - dXxD10 - D25	3/7.5
dXxD20 - D70 - dG10	10/4
dXxD70 - D10 - dG20	4/15

When either X or D contents in the X – dXxD – D system are equal to or below 15 vol. %, calculated coding is used (see the upper triangle in **Fig. 6.19**). Similarly (see the lower triangle in **Fig. 6.19**), calculated coding is applied in the dXxD – D – G system when either G is equal to or below 5 %, or, dXxD is equal or below 15 %. Examples are given in **Tab. 6.10**.

**Tab. 6.10:** Calculated coding for poly-component lithotype varieties composed of the neighbouring components. Note that in each case at least one of the components is below 15 vol. % and dG is equal to 5 %.

Composition	Calculation	Code (calc.)
X90 – dXxD5 – D5	$\frac{1}{100} * [(3 * 90) + (4 * 5) + (9.5 * 5)] = 3.38$	<b>3.38</b>
dXxD10 – D80 – dG10	$\frac{1}{100} * [(4 * 10) + (9.5 * 80) + (15 * 10)] = 9.50$	<b>9.50</b>
dXxD30 – D65 – dG5	$\frac{1}{100} * [(4 * 30) + (9.5 * 65) + (15 * 5)] = 8.13$	<b>8.13</b>
dXxD10 – D65 – dG25	$\frac{1}{100} * [(4 * 10) + (9.5 * 65) + (15 * 25)] = 10.33$	<b>10.33</b>

If heterogeneous poly-component lithotype varieties are composed of non-neighbouring components, then the two neighbouring components are expressed by one code value, while the remaining non-neighbouring component is coded by its source code. Combined codification of this type is cited in **Tab. 6.11**.

**Tab. 6.11:** Combined coding for poly-component lithotype varieties composed of the non-neighbouring components.

Composition	Code (comb.)
X25 – D55 – dG20	<b>10/3</b>
X65 – D10 – dG25	<b>3/15</b>

More than three component lithotype varieties are relatively rarely encountered at the basic lithotype logging. They are, however, more frequently obtained when average lithotype compositions are cited for lithologically generalized segments of lignite, as e.g. in **Figs. 6.26-a,b**.

In the case of heterogeneous X – dXxD – D – G compositions, which are expressed by combined codes, one code value is attributed to the D – G ratio and the other one to the X – dXxD ratio. Two examples are given in **Tab. 6.12** (note that the upper example is the composition of segment III of the JV-948-HI/2000 generalized borehole log in **Fig. 6.26-b**). Partial composition

D57 – dG5 in the upper example in **Tab. 6.12** corresponds to the ratio D92 – dG8 if recalculated to 100 %, and is therefore coded by source code 10. Code value 3.42 is a calculated code for the ratio between X and dXxD, which is X58 – dXxD42 if recalculated to 100%.

**Tab. 6.12:** Combined coding for four component lithotype varieties.

Composition	Code (comb.)
X22 – dXxD16 – D57 – dG5	10/3.42
X24 – dXxD33 – D16 – dG27	3.58/12.5

If also xylite is gelified, such composition is codified as e.g. shown in **Tab. 6.13**:

**Tab. 6.13:** Combined coding of a poly-component lithotype variety containing both xylo-gelite (xG) and detro-gelite (dG).

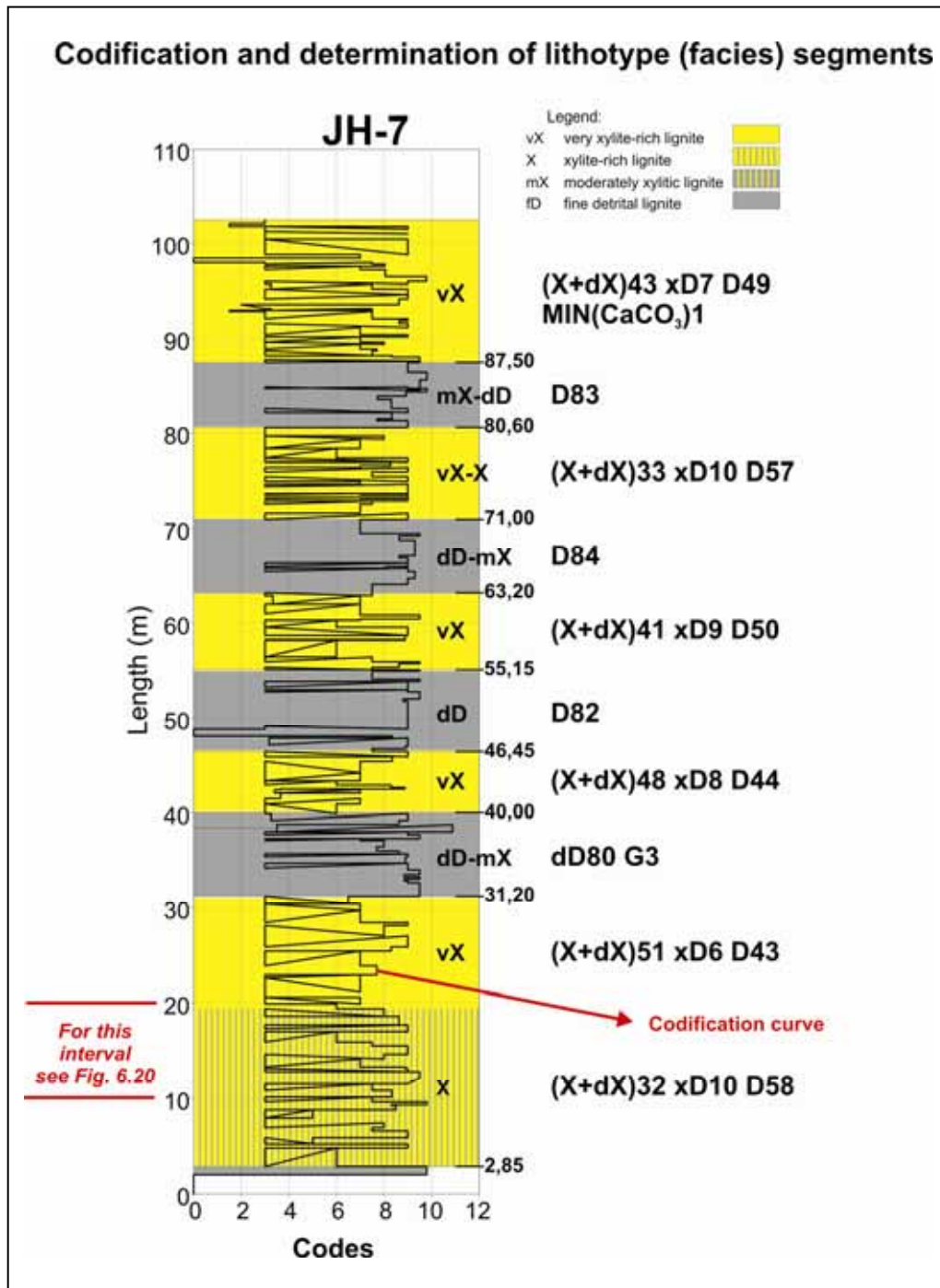
Composition	Code (comb.)
X17 – dXxD17 – D36 – dG18 – xG12	12.5/(3/15)/4

The first code of the composition in **Tab. 6.13**, i.e. 12.5, describes the most outstanding D – dG ratio in which the “share” of dG is 33 %; it is exactly in the middle (see **Fig. 6.18-a**) of the weak (g – code 10) and the pronounced (G – code 15) gelification. The combined code value written in parentheses (3/15) refers to the xylo-gelite which is expressed by both X and xG. In the xG – X ratio, the portion of xG is 41 % which means pronounced gelification and hence the attribution of code value 15. Code value 3 designates xylitic origin. The dXxD component is the lowest in its content (but still higher than 15 vol. %) and is therefore cited by source code 4 at the end of the whole code expression.

More uniform poly-component compositions, in which X component is equal to, or lower than 15 vol.%, and gelification dG as the other extreme is equal to, or lower than 5 %, are codified by calculated codes. Composition X8 – dXxD30 – D60 – DG2 of segment VI in JV 948 borehole in **Fig. 6.26-b**, which is coded by a calculated code of 7.44, can serve as an example. If the low content of X and the inconsiderable degree of gelification of fine-detrital matrix dG are neglected, a relative composition dXxD33 – D67 is obtained, coded by a source code of 7.5. Codes 7.44 and 7.5 are very close, thus explaining why it is reasonable to codify uniform poly-component compositions by one-number calculated codes.

Mineral matter is coded if it is estimated to exceed 15 vol. % in content. In combination with all other organic lithotype components, it is always cited separately by one of the source codes (1, 2 and 1.5, respectively) (**Fig. 6.18-a**). If the content of mineral matter does not reach 15 vol. %, the presence of mineral matter is merely noted.





**Fig. 6.21:** Petrographic log of the entire JH-7 borehole expressed by lithotype codification curve. Clearly visible is the alternation between homogeneous fine-detrital and heterogeneous more or less xylite-rich lignite layers. (For fine-detrital parts, only D (and G) contents are cited – the rest are different xylite-containing components).



### 6.3.2. Petrographic logging of lignite in borehole-cores

As already mentioned in **Chap. 5**, petrographic study of the Velenje lignite started in 1992, with the logging of core profiles from three structural boreholes: P-8z/92 (northern marginal area of the lignite seam), and P-9k/92 and P-12o/92 (central area of the lignite seam) (**Figs. 2.2** and **6.2**). Six years later, in 1998, a similar logging was also done on the borehole-core P-11r/98 in the central part of the basin. In total, the logged lignite cores of all four boreholes amounted to 285 metres. In P-8z/92, the lignite seam was only 15 m thick, whereas in other three wells its thickness ranged from about 85 to 100 m (**Fig. 2.4**). Petrographic logging was carried out following the terminology recommended at the time by the ICCP and soon after, in 1993, also officially accepted as the lithotype classification for soft brown coals (lignites) (in TAYLOR et al., 1998, p.280) (**Tab. 6.1**). Lithotype variability of lignite in the mentioned borehole-cores was the basis for sampling for a palette of further investigations.

The first report on the lignite petrography of the three boreholes from 1992 was written in 1993 (MARKIČ, 1993). A similar report for the lignite seam, together with micro-petrography of separate segments, was written for borehole P-11r/98 (MARKIČ et al, 2002), whereas macro-facies analysis and interpretation of sedimentary environments of the overlying and underlying sediments in this borehole was elaborated by SKABERNE (2000).

Petrographic logs of boreholes P-9k/92, P-8z/92 and P-11r/98 are shown in **Figs. 6.22, 6.23** and **6.24**.

A much greater extent of the lignite-core petrographic work was done on the underground boreholes. As many as 73 underground boreholes in a total length of 2250 meters were petrographically logged in detail since the mid 1990s. Two examples of petrographic logs of the underground borehole-cores are given in **Fig. 6.25**.

Structural boreholes were up to 10 cm in a diameter, while the underground ones between 4 and 6 cm. The dimensions mentioned are important as they represent limiting dimensions for petrographic description. Underground boreholes were mostly up to about 100 m long, one extreme, JV-768-H/98, even 167.2 m (**Fig. 6.26**). Due to careful drilling and permanent improvements in drilling techniques, core recovery (% of core) was mostly high. Core losses thus reflected unfavourable (“soft”) rock-mechanical conditions, either due to unfavourable lithological (lithotype) composition, or due to tectonically affected zones. Petrographic logs from structural boreholes were graphically documented at a scale of 1:100 and those from underground boreholes at a scale of 1:50.

During the whole study time from the early 1990s up to the present, approaches in lithotype characterization have altered. In general, the ICCP lithotype classification as shown in **Tab. 6.1** was followed at the beginning (**Figs. 6.22, 6.23** and **6.24**), whereas later an original concept of describing lignite by lithotype components and code values was established (**Figs. 6.20, 6.21, 6.25** and **6.26**) because of the fact that merely the use of the so called 10 % rule as typical for the ICCP classification (**Tab. 6.1**) was not sufficient for a more precise petrographic characterization of the lignite, especially in relation to a variety of subsequent analyses. An adopted lithotype classification and codification for the Velenje lignite as arising mainly from the borehole-core petrography was already presented in the previous **Chap. 6.3.1** and its sub-chapters.

## P-9k/92 – upper part

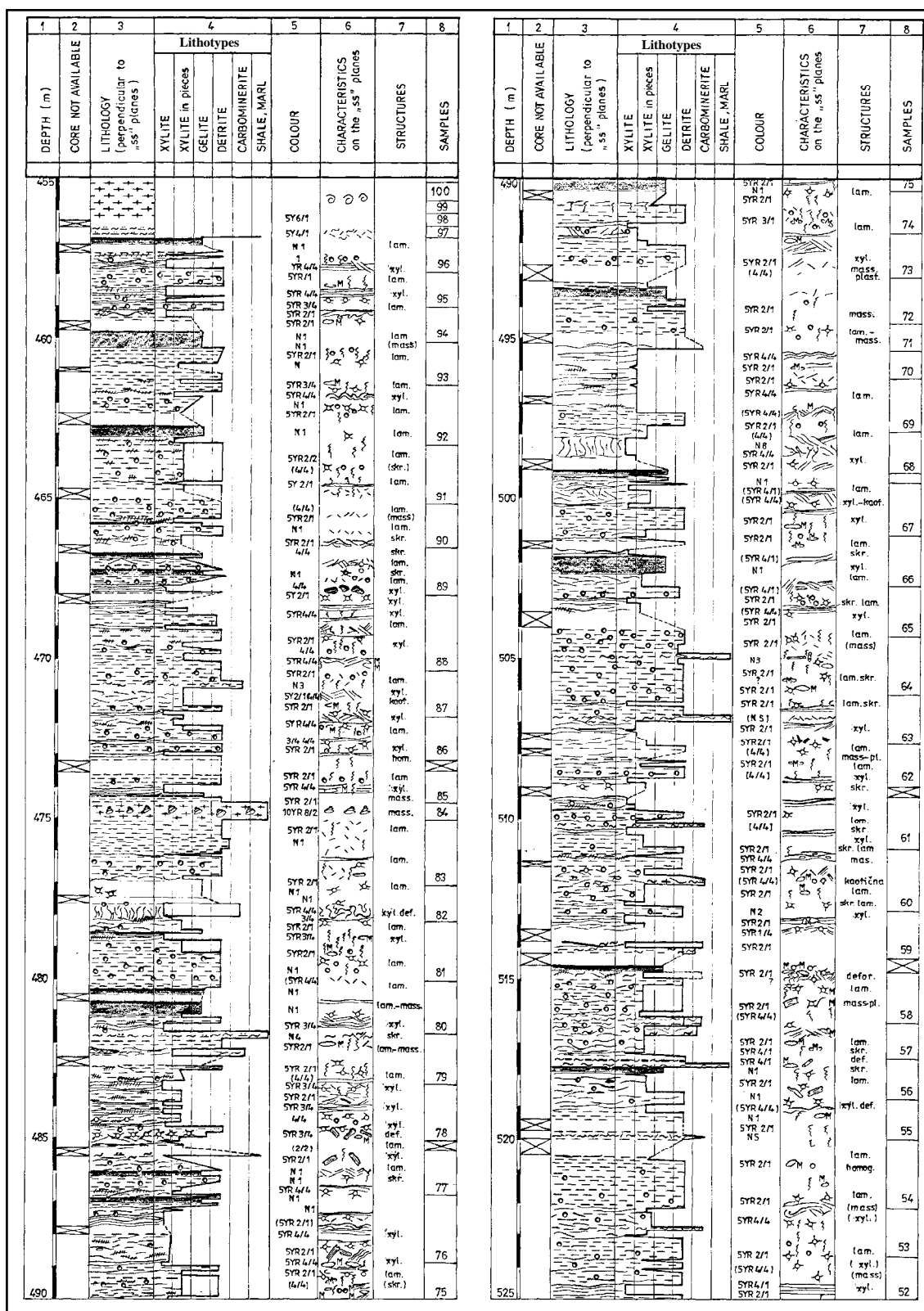
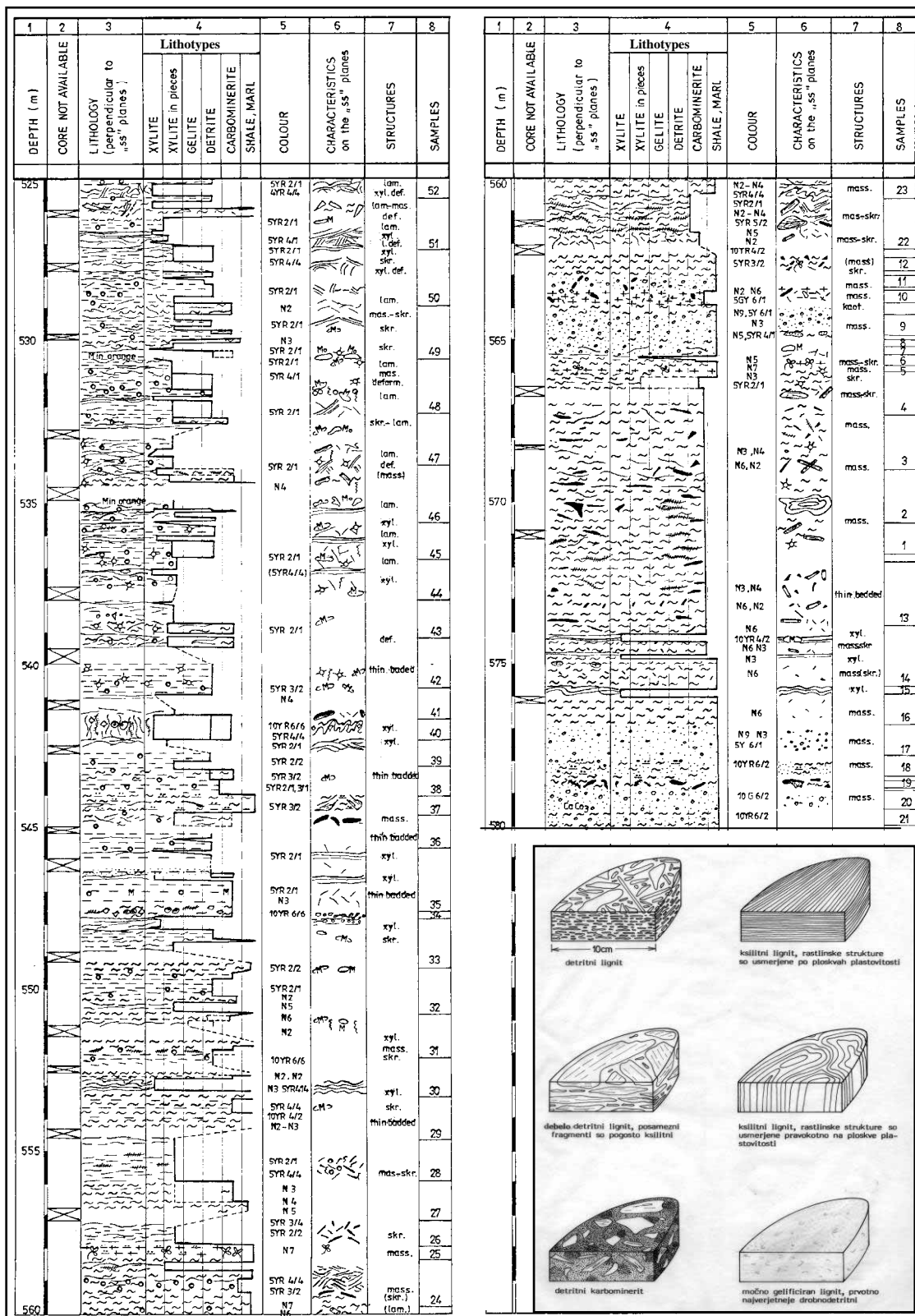


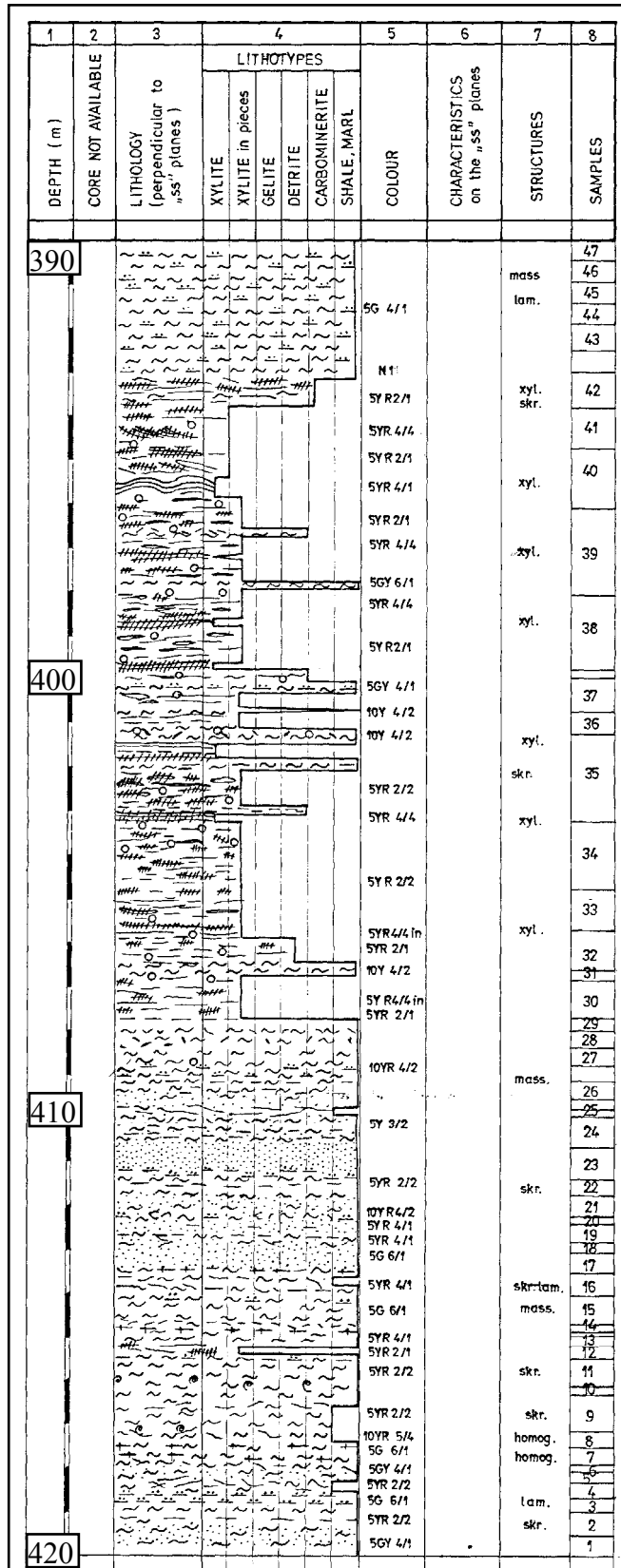
Fig. 6.22: Macro-petrographic log (seam profile analysis) of lignite in the P-9k/92 borehole-core. Terms for lithotypes (see the head of the columns) have the following meanings in respect to the ICCP (1993) classification in Tab. 6.1: "xylite" means *xylitic lignite* with >10 % of xylite which extends over core dimensions; "xylite in pieces" means the same as "xylite" but xylite pieces are smaller than core dimensions; "gelite" was used instead of "velenjit" sensu Hamrla from the 1950s, i.e. *gelified lignite*; "detritite" means

*detrital lignite*; "carbominerite" corresponds to *mineral-rich lignite*. Abbreviation "ss" means bedding plane (not very important for further discussion). For legend see Fig. 6.23. Some most typical lithotypes of the Velenje lignite are schematically shown at the bottom of the lower part of the P-9k/92 core log.

**P-9k/92 – lower part – Fig.6.3 continuation**



## P-8z/92



## Legend

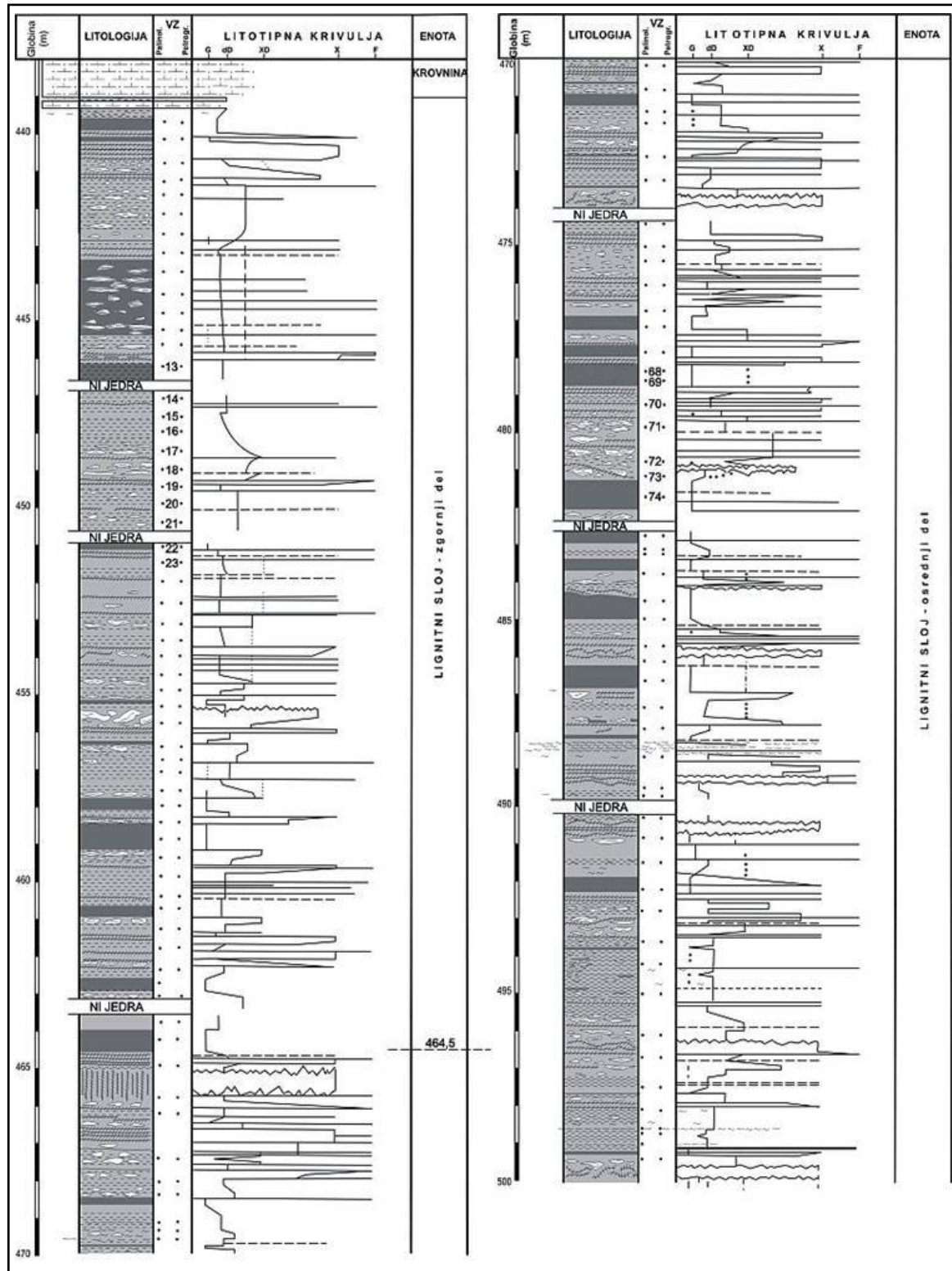
## of lithotype components as logged in structural boreholes

- Detrital lignite, mostly laminated, non-deformed
- Detrital and xylo-detrital lignite, laminated, non-deformed
- Detrital and xylo-detrital lignite, deformed, with slickensides
- Strongly gelified lignite, (detrital in origin)
- Gelified xylitic particles in mineral-rich matrix
- Xylite, non-deformed structure
- Xylite, deformed
- Detrital and xylitic lignite, brown
- Xylite in vertical (growth) position in the seam
- Fusite
- Orange mineral spots (anhidrit)

## Some additional petrographic characteristics as visible on the bedding ("ss") planes

- Xylite, non-deformed
- Xylite-rich lignite, chaotic structure
- Detritus
- Fragments of stalks, twigs, branchelets etc.
- Orange mineral spots and fusinite
- Olive-green mineral matter over plant remnants
- Macro-flora (mostly leaves) and micro-fauna (molluscs)
- Spheroids

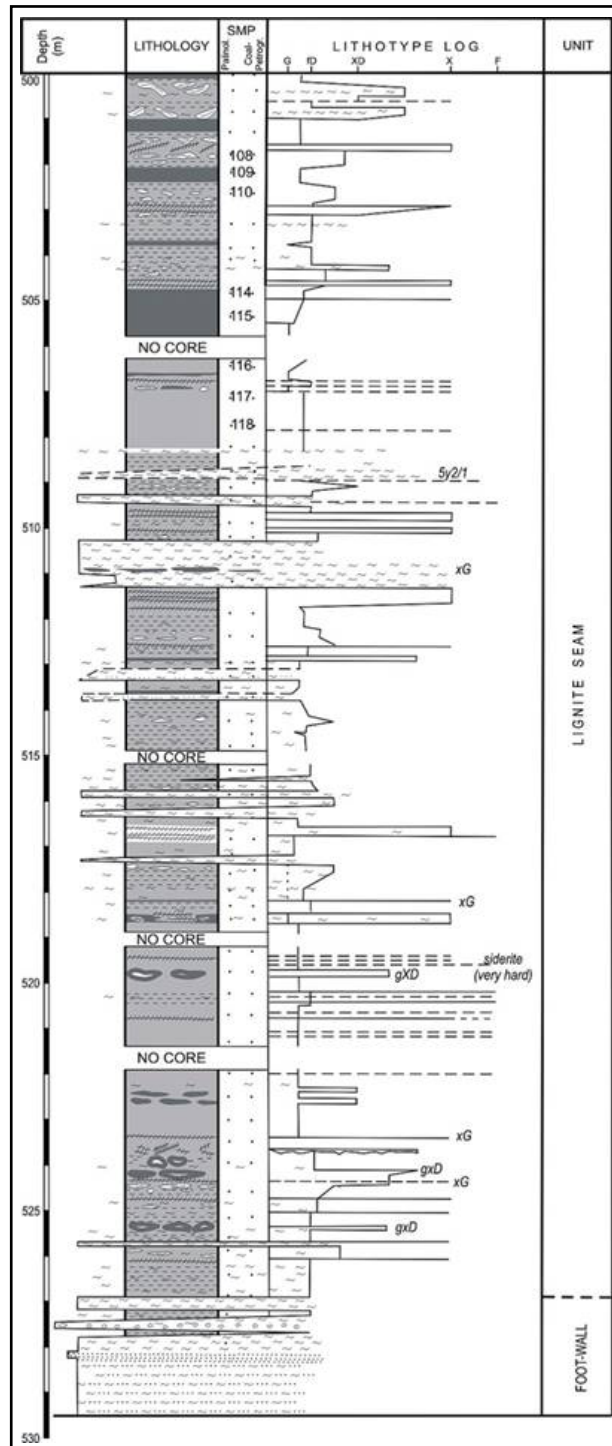
**Fig. 6.23:** Macro-petrographic log of lignite in the P-8z/92 borehole-core. Terms for lithotypes are the same as in the P-9k/92 borehole in Fig. 6.22.

**P-11r/98 – upper part** (see for English the lower part)


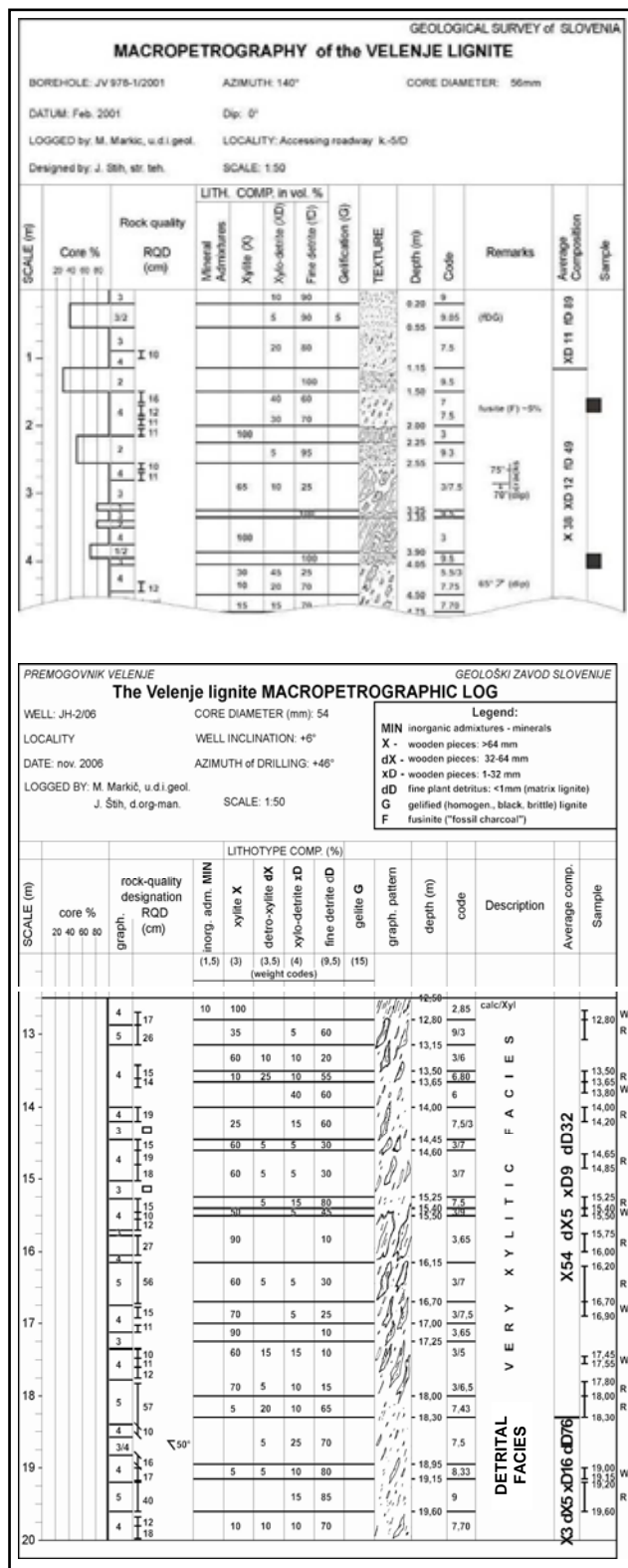
**Fig. 6.24:** Macro-petrographic log (seam profile analysis) of lignite in the P-11r/98 borehole-core. Abbreviations for lithotypes signify: G – gelite, i.e. **gelified lignite**; dD – fine detrite, i.e. **detrital lignite**; X – xylite as in the P-9k/92 log in **Fig. 6.22**, i.e. **xylitic lignite**; XD – xylite-detrite as “xylite in pieces” in the P-9k/92 log i.e. **xylitic lignite** as well; F – fusite i.e. **fusitic lignite**. Abbreviations such as gXD and xG in the lower part of the seam signify gelified (g) xylo-detrite pieces and very gelified (G) xylite, respectively. It is

important to note the succession of lithotypes, from originating in more “water-logging” and anaerobic conditions on the left (with G as one extreme) to more aerobic on the right (with F as another extreme), and thus holding greater genetic consideration than in the case of lignite core P-9k/92 in Fig 6.22. Note also the presentation of mineral partings to the left of the column of more or less pure coal.

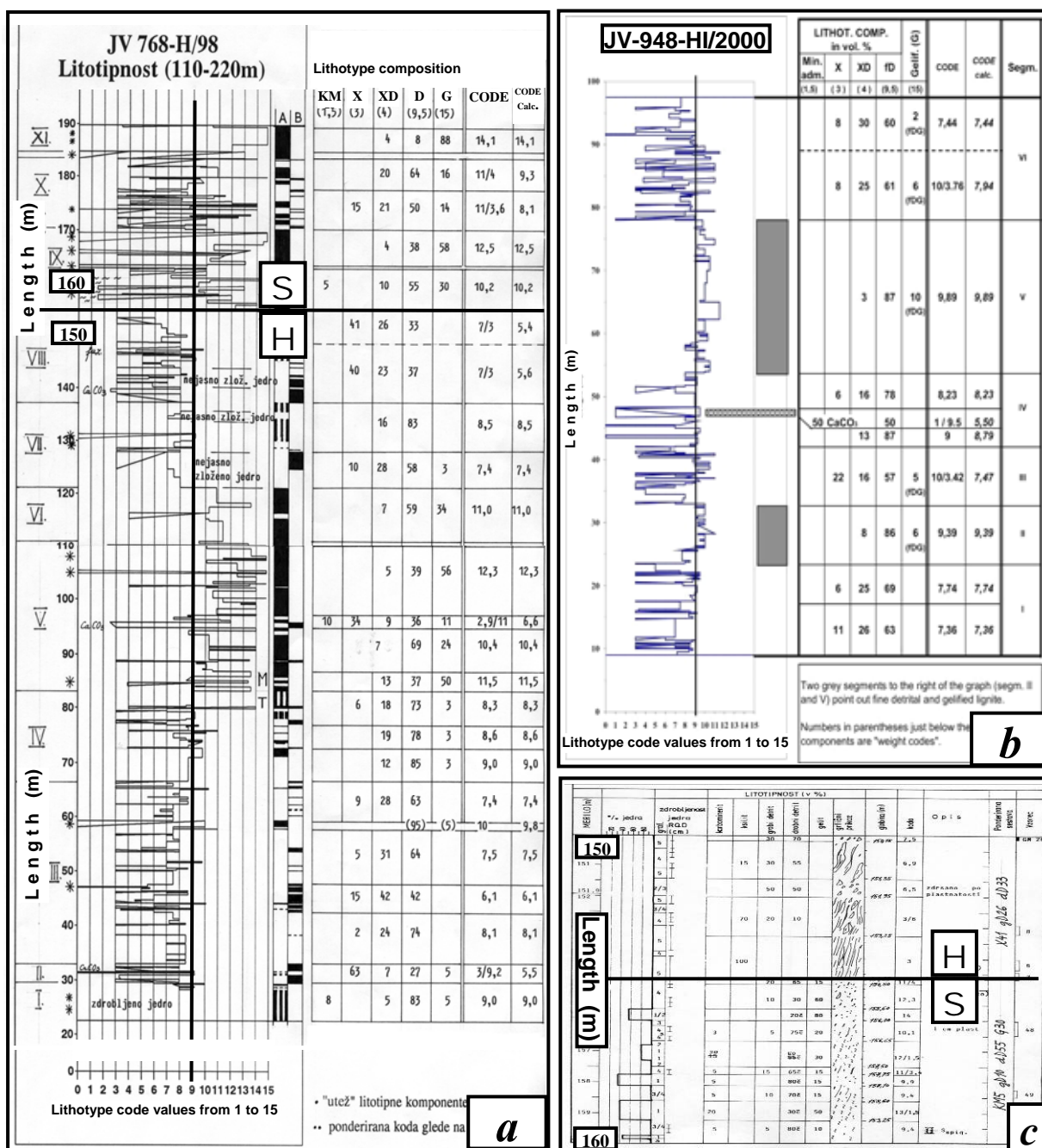
### P-11r/98 – lower part







**Fig. 6.25:** Macro-petrographic logs of two underground boreholes drilled horizontally. Lithotype characterization is expressed by the composition and texture of lignite. The composition is given by lithotype components in vol. % and by code values (see more in **Chap. 6.3.1** and its sub-chapters). Texture (size, shape, and orientation of the lignite ingredients) is presented graphically. In both cores, segments of xylite-rich and segments of fine-detrital lignite can be clearly separated. Note also the very low angle between the bedding and the drilling inclination.



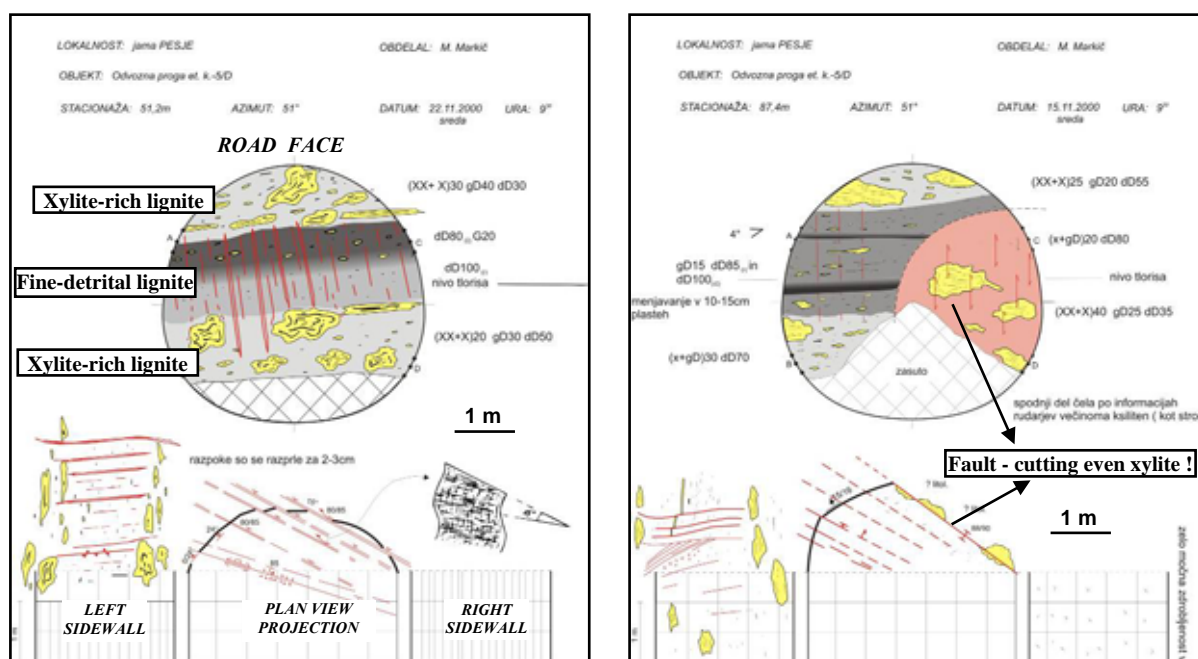
**Fig. 6.26:** a) and b) Macro-petrographic logs of the whole ca.170 and ca.100 meter long borehole-cores JV-768-H/98 and JV-948-HI/2000. Both boreholes were drilled (semi)horizontally (ca. +5°). Lignite in both cores is divided into several segments (marked by roman numbers). It is important to distinguish between segments of homogeneous (and gelified) fine-detrital lignite with code values >9, and more or less xylite-rich heterogeneous segments marked by code values between 3 and 9. c) A detail from the original petrographic log sheet (JV-768-H/98) at the transition from the xylite-rich into the fine-detrital lignite, which is also termed in the mining jargon as the transition “from the hard (H) into the soft (S)” lignite.

### 6.3.3. Petrographic mapping of lignite in the underground mine workings

The main advantage of petrographic mapping of underground road-faces and long-walls is that relatively large surfaces of lignite can be observed. Two photos of the road-faces are given in **Fig. 6.27**; two geologically documented road-faces are presented in **Fig. 6.28**, and two long-walls in **Fig. 6.29**. In such objects, structural elements like bedding, banding, lamination, and/or different irregular masses of lignite are described first. Systems of cleats and joints may be of



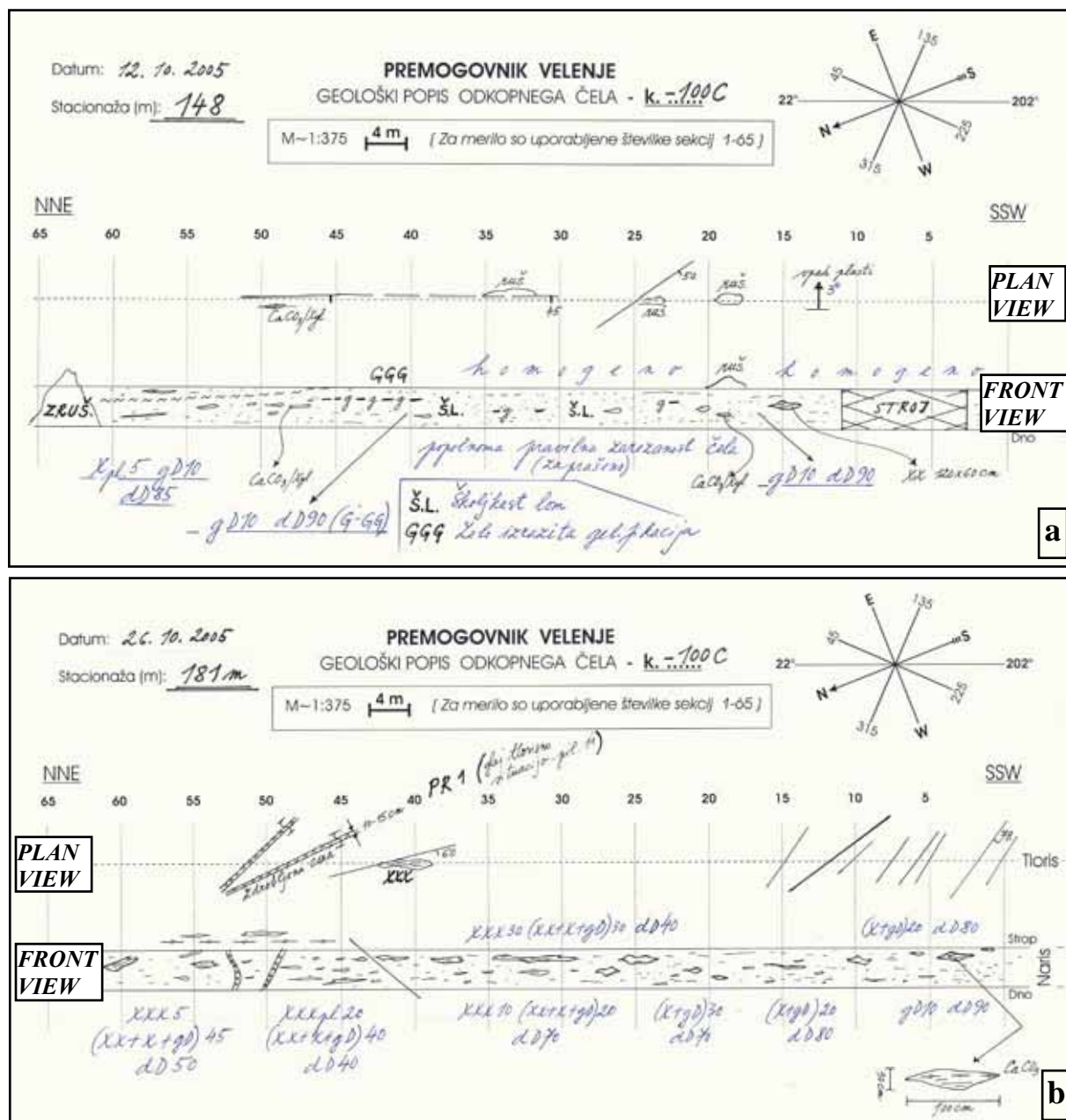
**Fig. 6.27:** Two mining road-faces, ca 4×4 m wide. The sidewalls are covered by wooden planks.



**Fig. 6.28:** Two geologically documented road-faces (other two than in **Fig. 6.27**). Contrasted layers of xylite-rich and of fine-detrital lignite are clearly distinguishable in both faces. Note the different sizes, shapes, packing and orientation of xylite pieces and lumps within fine-detrital matrix (niances of gray). Strongly gelified layers are shown in black. Joints and fissures are most frequent in gelified and fine-detrital lignite, whereas they disappear in xylite-rich lignite. In the right face, a fault, which cuts even the biggest xylite lumps is worth mentioning.



considerable help to delineate separate layers from some distance. Petrographic composition of different units is subsequently evaluated by the contents of lithotype components. Coding is generally not practiced. This is because petrographic data as observed in mine workings are – due to generally poor working conditions (lighting, dust, time pressure) – less detailed than those from borehole-cores. Tectonic elements such as faults, cracks and fissures, internal deformations due to sliding and compaction are documented as well.



**Fig. 6.29:** Lignite petrography and tectonic elements as documented along two ca. 100-m wide long-walls. An advantage of this kind of mapping is the broadest spatial insight into the lignite gross composition, structure, texture and tectonics, whereas bad visibility and dangerous conditions at close observations are often critical. **a)** The long-wall is within gelified (g to GGG) fine-detrital lignite with pronounced conchoidal fracture (Š.L.). **b)** This long-wall runs within more xylite-rich lignite. At some places, replacements of xylite by calcite have been noticed. Note also a prominent tectonic zone passing the NNE side of the long-wall (for a wider situation, see **Figs. 6.35** and **6.38**).

### 6.3.3.1. Reasons for underground lignite mapping

Macro-petrographic study of lignite in the Velenje underground mine workings commenced in 1996. This was to a great part the result of the fact that, after initial macro- and micro-petrographic studies of lignite, interest for a petrographic study of lignite arose also among the leading mining and geology experts at the VLM. It was quickly realized that spatial mapping of petrographic heterogeneity may help to a better understanding of rock-mechanical properties, including problems related to lignite-bed gases. The starting point of the investigations was based on the assumption that different lithotypes have different rock-mechanical properties as well as different properties with regard to gas accumulation, sorption, permeability etc. In this sense, e.g. JEREMIC (1985, p.70 – after PROTODYAKONOV, 1965) pointed out: "The most important fact with respect to rock-mechanics in coal mining is that each lithotype has particular mechanical properties and behaviours which might cause instability of coal seams, if they are represented in broad bands".

Thus, the main aim of applied gross petrographic study was to better understand and define spatial petrographic parameters that can more or less increase the proneness of different lithotype varieties to coal and/or gas outbursts. On the basis of the mining experience concerning coal and gas outbursts (LIKAR, 1995), and on the basis of preliminary laboratory results concerning gas adsorption and desorption properties of different lithotypes (ZAPUŠEK & HOČEVAR, 1998; PEZDIČ et al. 1999), it was supposed that especially fine-detrital gelified varieties are critical from this point of view, particularly when occurring in thick layers or irregular bodies. Beside the outbursts, fine-detrital gelified masses of lignite are unfavourable with respect to mine stability conditions as well. If mine workings pass areas with unfavourable fine-detrital and gelified lignite, such conditions are termed "soft" conditions in the Velenje mining jargon. In contrast to the fine-detrital gelified lignite, xylite-rich lignite is very tough and hard to break. Mining conditions in xylite-rich lignite with good cohesion between xylitic fragments and fine-detrital matrix are considerably more stable and therefore termed "hard". They are mostly not dangerous with respect to the occurrence of gas outbursts. Dangerous situations occur when mine workings suddenly pass from "hard" to "soft" lignite – especially when such contacts are sharp and connected to fault zones (ZAVŠEK et al., 1997). The importance of the "hard" / "soft" transitions was also pointed out by JEREMIC (1985, p.186) who stated that: "existence of large pockets of weak porous coal (in our case: "soft" gelified lignite) surrounded by strong heterogeneous coal (in our case: "hard" xylite-rich lignite) or vice versa can facilitate coal and gas outbursts after de-stressing of coal seams".

The petrographic investigation of lignite in underground workings started in 1996 in the NE sector (**Fig. 6.2**), where the lignite seam lies closely above the water-bearing Triassic dolomite. Because mining was abandoned there soon after 1996, mapping was focused then on the southern side of the lignite mine within the Preloge and the Pesje sectors (**Fig. 6.2**). Mapping distribution was dependant on the planning and development of mine workings, i.e. accessing roads, long-wall faces and boreholes. Up to the present, the mapping of mine workings involved more than 3700 metres of mining roads, which were sketched and described by more than 200 road-faces.

### 6.3.3.2. Characteristics of the objects mapped

Petrography in the underground mine workings involved petrographic and tecto-structural sketching of lignite as visible in road-faces (**Fig. 6.28**) and long-wall faces (**Fig. 6.29**). Road-

faces were oval in outline, 4 m high and 4 m wide. Roadway sidewalls were obstructed by wooden boards immediately after each advance. Therefore, sidewalls could not be documented in intervals longer than 1 to 2 m. Documentation was made in the same scale as for borehole-cores – 1:50, but the working conditions were worse. Lithotype characterization in mine workings was therefore less precise and accurate than in the borehole-cores. Long-walls were about 100 m long and more than 4–5 m high. Mapping was done during the time of the working team exchange, at midday, in approximately one hour. Mapping of long-walls was much less extensive than the road-face mapping in the advancement roads.

Petrographic profiles along the mining roads were done by data correlation between the road-faces, which were mostly more than 10–20 m apart. Reports of the miners at the working sites helped a lot to get additional information about the lignite which could not be observed directly. In the cases where also data from borehole-cores were available, lithofacies presentations could be widened outward from the mine roadways – into their roof and floor strata respectively. In the continuation, some examples of lithofacies and tectonic interpretations along mine workings will be presented.

### **6.3.3.3. Selected examples of structural petrographic and tectonic interpretations at different localities of mining within the Velenje lignite seam**

#### **6.3.3.3.1. Incline and the mining road to access the exploitation field D at the -5 height level in the Pesje sector**

The first two examples will be two segments of the accessing mining objects for lignite exploitation at height level -5 in the Pesje sector (two green circles in **Fig. 6.30-b**). The SW-ern circle indicates the location of an incline running from the height level -43 upwards to the level -5, where the exploitation (in the D field) was planned. The NE-ern circle marks an area of the accessing mining road Et.k.-5/D, which is shown more in detail in **Fig. 6.30-a**. The presentation of geological situation in the -43/-5 incline is chosen, because it shows an interpretation based on the road-face petrographic data and the JV-948-HI/2000 borehole-core data. The presentation of the geological situation in the Et.k.-5/D road (true level -10) is interesting, because about 15 m below of it, in the former mining road at level -25, a huge coal-and-gas outburst happened in 1962 (**Fig. 6.30-a**).

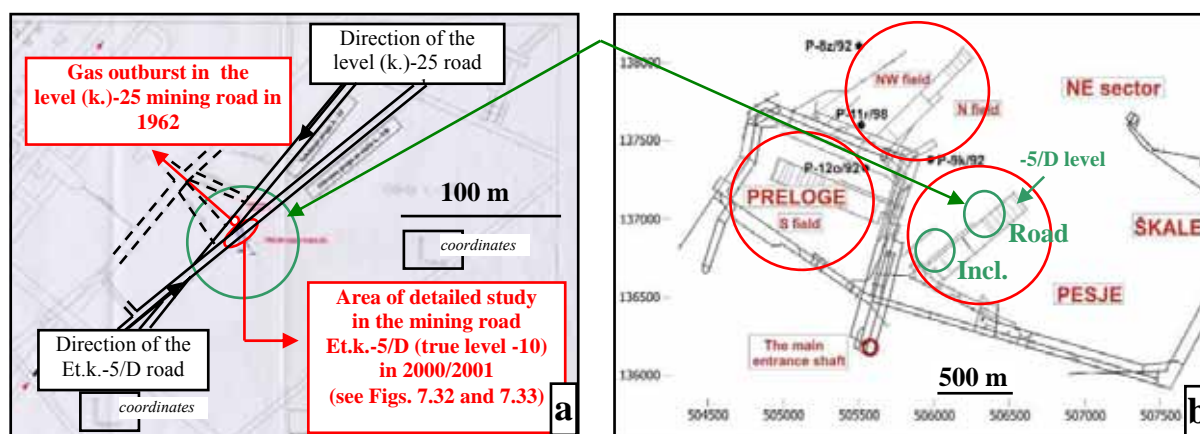
A spatial interpretation of lignite facies heterogeneity in the area of the -43/-5 incline and borehole JV-948-HI/2000 is given in **Fig. 6.31**. The incline ran 12 to 24 m below the hanging-wall<sup>29</sup>/lignite (HW/L) contact and passed a strong tectonic zone at its lower (starting) part. In this zone, strongly crushed lignite was detected above the incline's ceiling. The lignite in the road-face at 32.7 m was xylitic, quite heterogeneous in composition, but not internally deformed (as in cases of the faces in the continuation). These two facts, together with the evidence of the displacement of the HW/L contact, clearly imply post-lignite-depositional tectonic activity. The lineation of tectonic structures was not clarified due to non-existent data in the neighbourhood mining objects and due to difficulties connected with the possibility to carry out more exact in situ measurements of the tectonic elements. In the continuation of the

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<sup>29</sup> Hanging-wall – a term from the mining jargon used here for the roof strata lying just above the lignite seam.

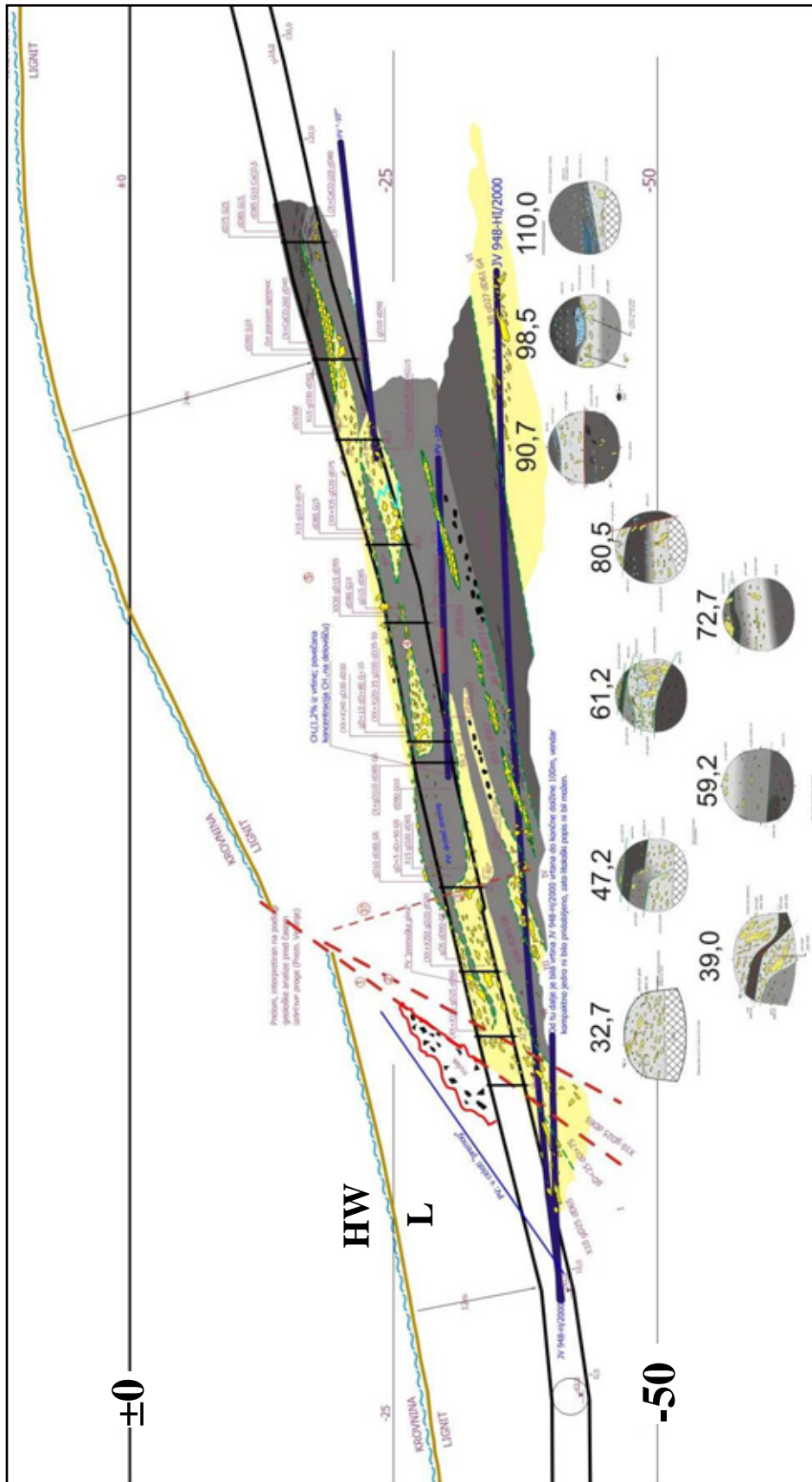


incline, quite a contrasted lithotype composition of different layers or “more irregular bodies” was detected. As seen from **Fig 6.31**, lithotype composition of the lignite within the incline varied from xylite-rich (in yellow) to fine-detrital (grey) and gelified (dark grey to black). Chaotically distributed xylite fragments of different dimensions and shapes as frequently observed in the road-faces suggest quite labile zones already at the time of deposition. Deformations as registered in the road-faces at 39.0, 47.2, 61.2., 72.7, 90.7 and 98.5 m clearly show syn-sedimentary deformations caused by the loading and sinking of heavier (and harder) masses (e.g. xylitic stumps and calcified woods) into the softer fine-detrital organic sediment, by growth (flexure) faulting, and by local compaction, sliding and squeezing of different masses due to local compression/relaxation stresses and local topographic instabilities.



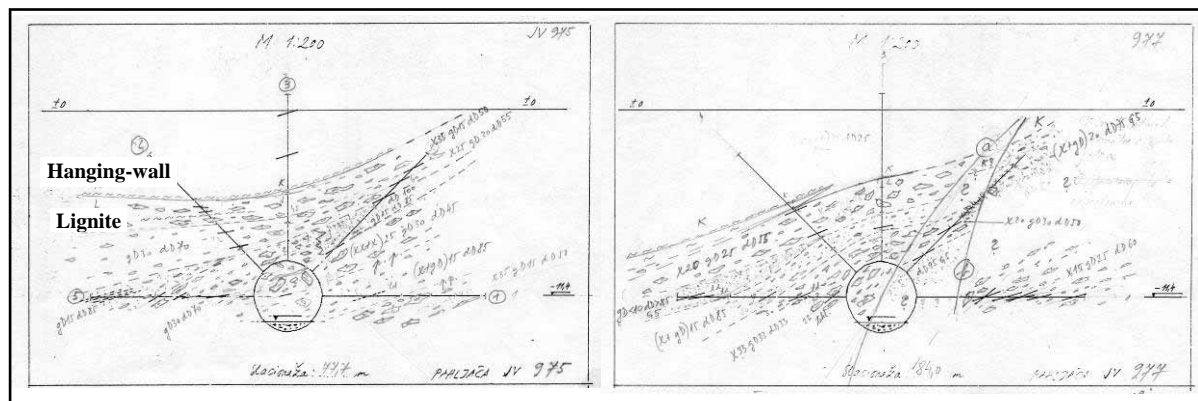
**Fig. 6.30:** **a)** Situation of the mining road “level -25” from 1962 and the mining road “Et.k.-5/D” (true level -10) from 2000. The locality of a gas outburst in the -25 level road in 1962, and the section in the Et.k.-5/D road thoroughly studied in 2000/01, are indicated. The first attempt to study the gas outburst location was carried out with four boreholes (dashed lines) in 1998). **b)** Situation of the accessing objects for lignite exploitation at the height level -5 in sector Pesje. The -43/-5 mining incline and the Et.k.-5/D mining road are indicated by two small circles (“incline” and “road”).

The JV-948-HI/2000 borehole was drilled horizontally, ca. 100 m long. The spatial lithofacies picture is self-explanatory from **Fig. 6.31**. For a detailed petrographic log, the reader is referred to **Fig. 6.26-b**. What is interesting in this borehole is the occurrence of the carbonate layer (at its 48 m length) characterized as dark grey organic-rich limestone. A similar layer, most probably of the same sedimentary horizon, was reported from a borehole drilled ca. 6 m above (PV -10°). Further on, a limestone lens (appertaining to an upper carbonate horizon) was registered in the incline at 98.5 and 110.0 m as well. In all cases, the limestone lenses were encountered within fine-detrital lignite facies, lignite being weakly to moderately gelified. The relation between alkaline environment due to carbonate presence and enhanced gelification is therefore evident in the petrographic profile in **Fig. 6.31**.



**Fig. 6.31:** Structural petrographic profile along the -43/-5 incline and borehole JV 948-HI/2000, and sketches of the faces. Xylite-rich layers and xylite lumps are coloured in yellow (or in very pale gray in grayscale). Fine-detrital lignite is coloured in gray – increasingly dark with increasing content of the fine-detrital lithotype component and gelification degree. HW- hanging-wall; L- lignite. Fault zone at the lower part of the incline, different deformations and faults as recorded in the road-faces, and deformation of the HW – L boundary reflect a quite tectonically affected area.

The accessing road Et.k.-5/D, in the section where an outburst of coal and gas occurred ca. 15 m below in 1962, represents one of the most thoroughly investigated localities in the whole mine. The mining road Et.k-5/D passed this zone in November 2000. A programme of 40 boreholes in a total length of more than 400 m was carried out together with the mapping of the road-faces. The boreholes were drilled in 8 fans, at every 4 m of the road, each fan including five ten-meter-long boreholes. The boreholes were completely cored and petrographically logged (**Fig. 6.32**).



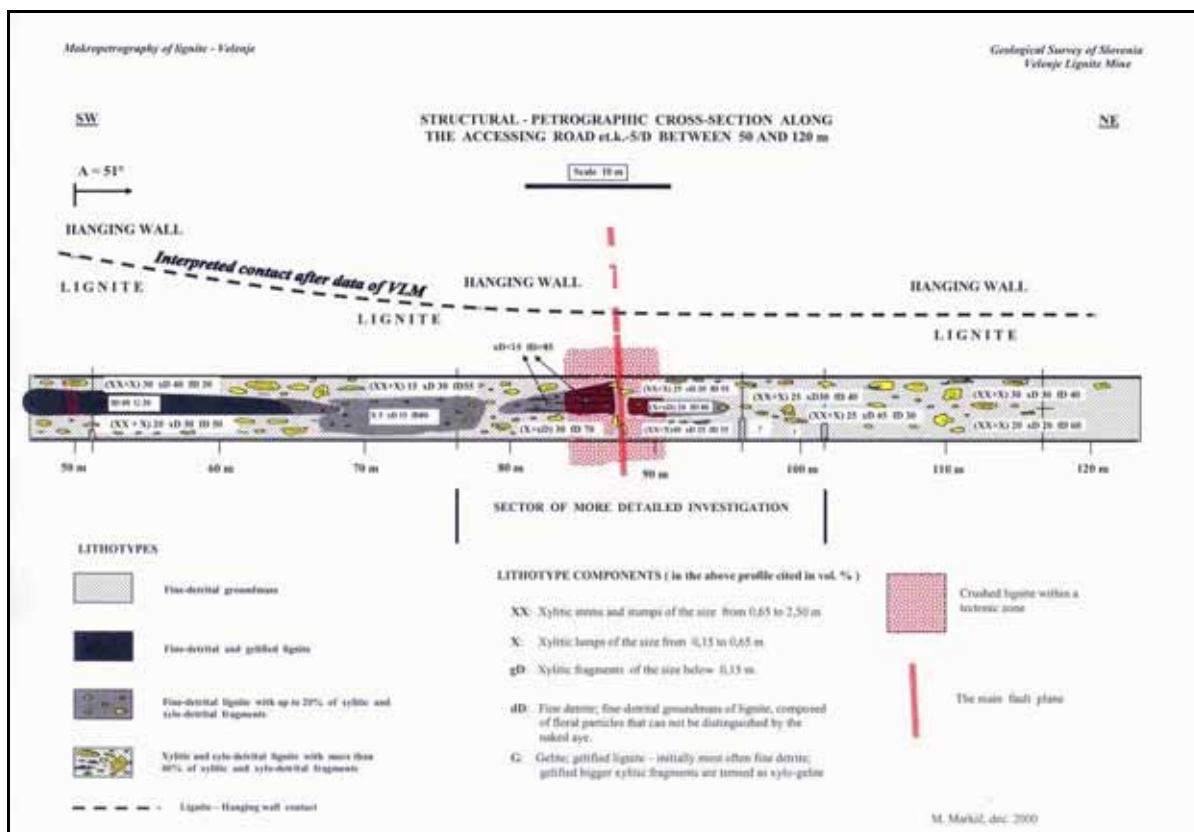
**Fig. 6.32:** An example of structural-petrographic and tectonic interpretation at two localities of the fan drilling in the Et.k.-5/D mining road. Such detailed assistant interpretations were the basis for synthetic profile construction as shown in **Fig. 6.31**. (For the scale, note the distance between levels  $\pm 0$  and  $-11.4$ ).

Before drilling, a prognostic profile as shown in **Fig. 6.33** was constructed based on the mapped road-faces. The fault zone in the middle of this profile was registered – besides in the road-face at 87.4 m (**Fig. 6.34**) – also by inspection of “rock quality” as possible to be seen behind the obstruction woods. The zone of the tectonically crushed lignite was ascertained to run in the N–S direction and to be ca. 5 m wide. It was also realized that the lignite SW of the fault consists of both the fine-detrital and the xylite-rich varieties, whereas on the NE side it consists of the xylite-rich lignite only. As seen from **Fig. 6.33**, after data provided by the mine's geodetic service, the road ran quite close below the hanging-wall/lignite contact.

A detailed structural-tectonic and structural-petrographic interpretation of the Et.k.-5/D road in the drilling zone is presented in **Fig. 6.34**. It shows the exact situation on both sides of the tectonic zone within which the coal and gas outburst occurred 15 m below. The situation is based on both the data from road-faces (at three sites) and the data from borehole logging.

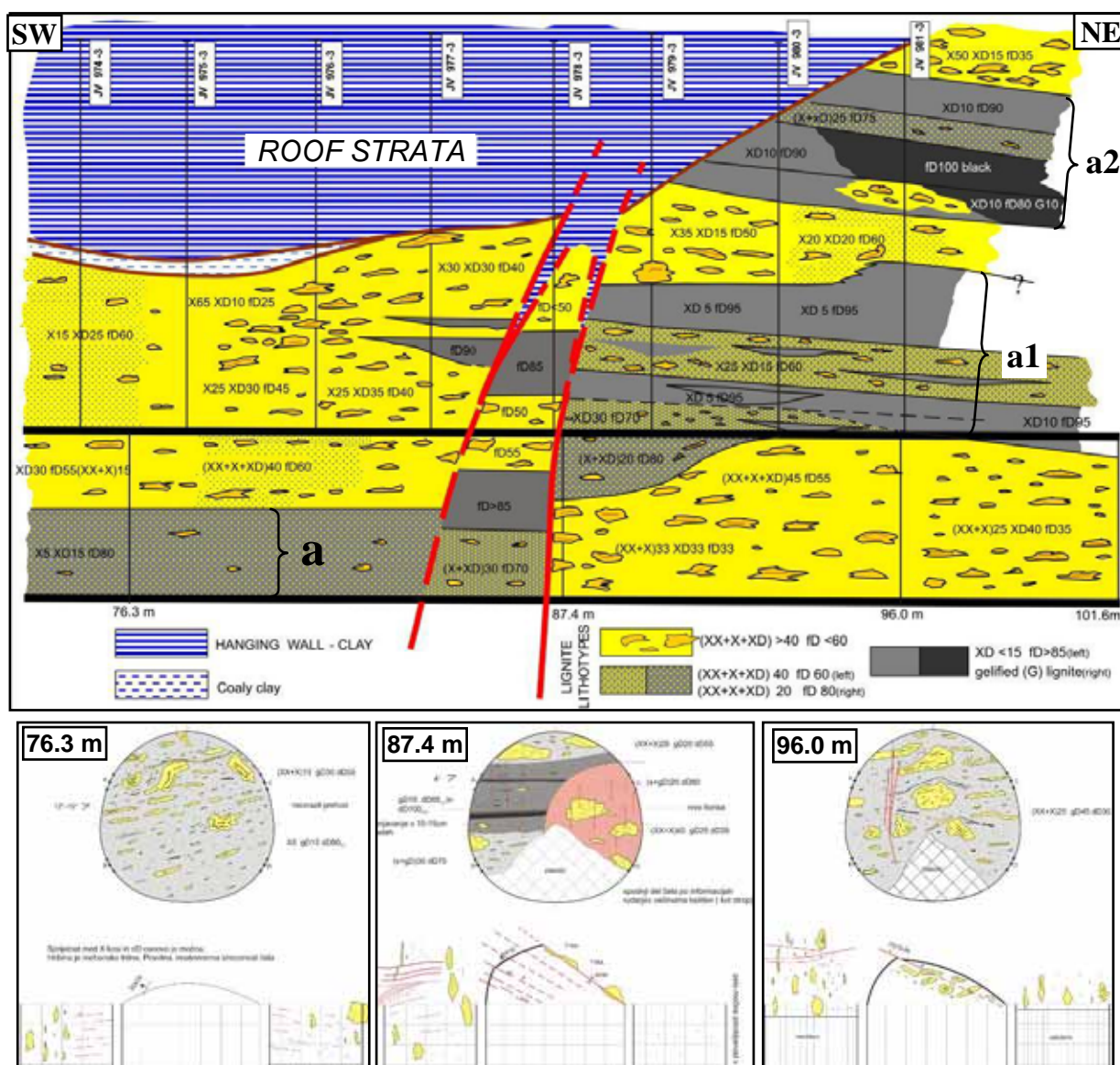
The petrographic interpretation in **Fig. 6.34** shows that before passing the tectonic zone, on the SW side, the road was running through a xylite-rich lignite (upper part of the road) and a xylite-poor to fine-detrital (fD80) lignite (marked by “a”). The lignite above the road was ascertained to be xylite-rich, whereas no data exist for the lignite below the road. On the other, NE side of the fault zone, the road entered entirely into the xylite-rich lignite. No data exist for the lignite below the road also for this section, whereas above the road, two bed-sets of prevailing fine-detrital lignite, marked by “a1” and “a2”, were proved by borehole data. The tectonic zone as shown by two main fault planes in **Fig. 6.34** was defined with a high certainty on the basis of “rock (lignite) quality designation” as inspected in the sidewalls of the road (crushed versus compact lignite), on the basis of the road-face data at 87.4 m, and on the basis of data from the borehole-cores. In the road-face, the tectonic plane cut also the largest xylite lumps. The cutting of large xylites by fractures is rare, but if so, this is a clear

evidence of severe post-depositional (post-compactional) faulting. With a high certainty, also the hanging-wall/lignite contact was proved, running considerably differently than previously interpreted in **Fig. 6.33**. In spite of the data density, the question of the range of the tectonic displacement remained unsolved. Namely, the bed-sets of fine-detrital lignite “a1” and “a2” on the NE side of the fault zone can be both correlated with the “a” fine-detrital lignite on the opposite side of the fault. In the first case (a-a1 correlation), vertical displacement can be estimated to about 4 m, whereas in the second one (a-a2 correlation) even to 8 m. The second interpretation seems to be more probable.



**Fig. 6.33:** Structural-petrographic profile along the Et.k.-5/D mining road interpreted on the basis of mapping of road-faces before the fan drilling was carried out. Road-faces are marked by vertical lines cutting the road at ca 52 m, 76 m etc. It is notable that the lignite on the SW side of the fault consists of the xylitic plus fine-detrital lignite, whereas on the other side of the fault of the xylite-rich lignite only. Older abbreviations for lithotype components (see **Tab. 6.4**) are cited in this profile.





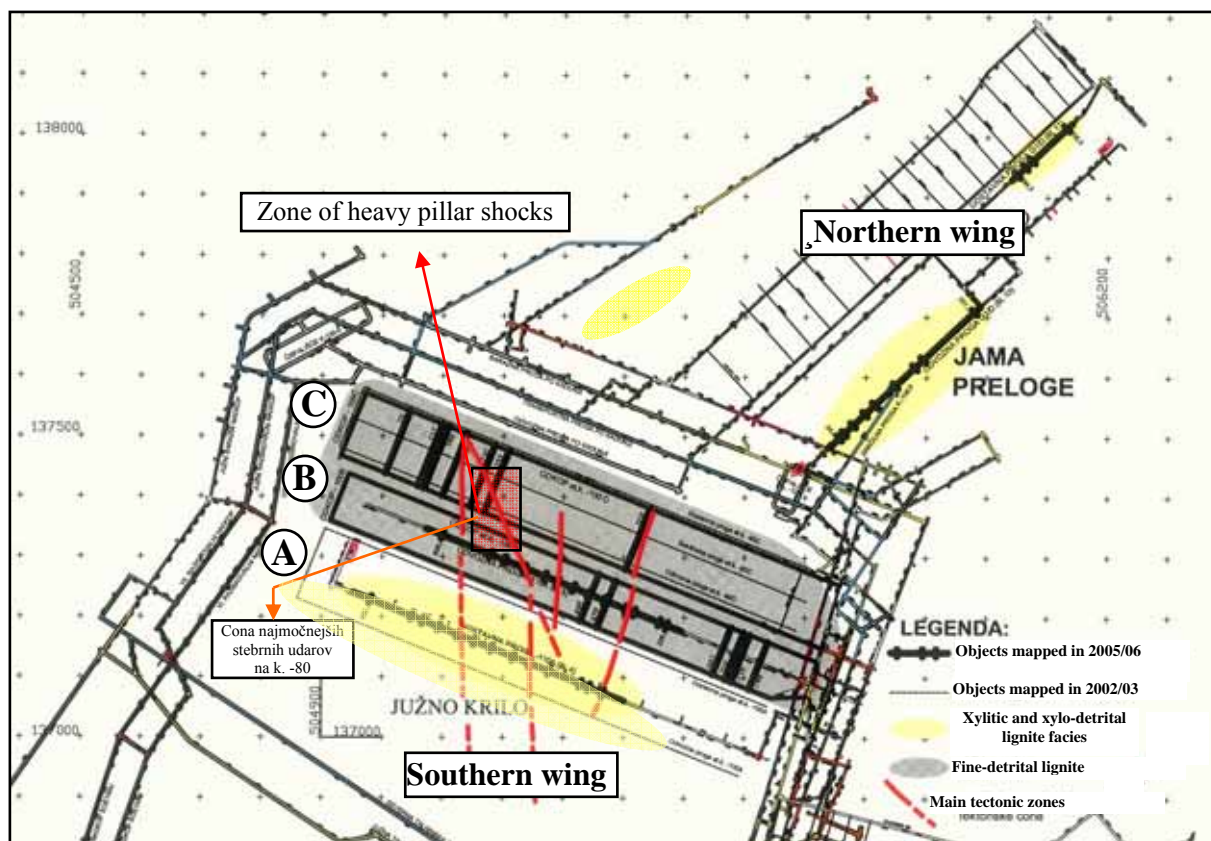
**Fig. 6.34:** Structural-petrographic and tectonic interpretation in a section of the Et.k.-5/D mining roadway (above) based on data from road-faces (below) and a set of eight borehole fans (see Fig. 6.32) of which only vertical boreholes are shown in the profile. This section was thoroughly studied because one of the hugest gas outbursts happened in 1962 in the road on level -25, i.e. ca. 15 m below this situation – most probably within the fault zone clearly visible in the road-face at 87.4 m. On both sides of the fault zone, dislocation of the strata can be best estimated by the dislocation of the fine-detrital lignite (read more in the text).

### 6.3.3.3.2. Mining roads and long-walls in the Preloge sector

A wide programme of underground mapping was carried out in the southern wing of the Preloge sector – by mapping mining roads and long-walls on levels -80, -90, -100, and -110. (Mapping on level -80, running 10–20 m below the hanging-wall/lignite contact, was restricted to shorter sectors and will be mostly omitted here). In the northern wing of the Preloge sector some road sections were also mapped.

The whole situation of mining objects in the Preloge sector, together with general lignite facies and tectonic features, is shown in Fig. 6.35. Detailed documentation involving road-face and long-wall geological sketches as well as profiles along separate mining roads is

enclosed in the annual working reports for the Velenje Lignite Mine (VLM) (MARKIČ et al. 2000, 2001a, b, 2002, 2003, 2004, 2005, and 2006). The studied area of the Preloge sector – the southern wing – encompasses three exploitation fields, the so called A (southernmost), B (middle), and the C (northernmost) field. An analogous division existed for the above exploitation fields as well. The southernmost A fields are developed within the peripheral part of the lignite seam, whereas B and C are developed toward its central part.

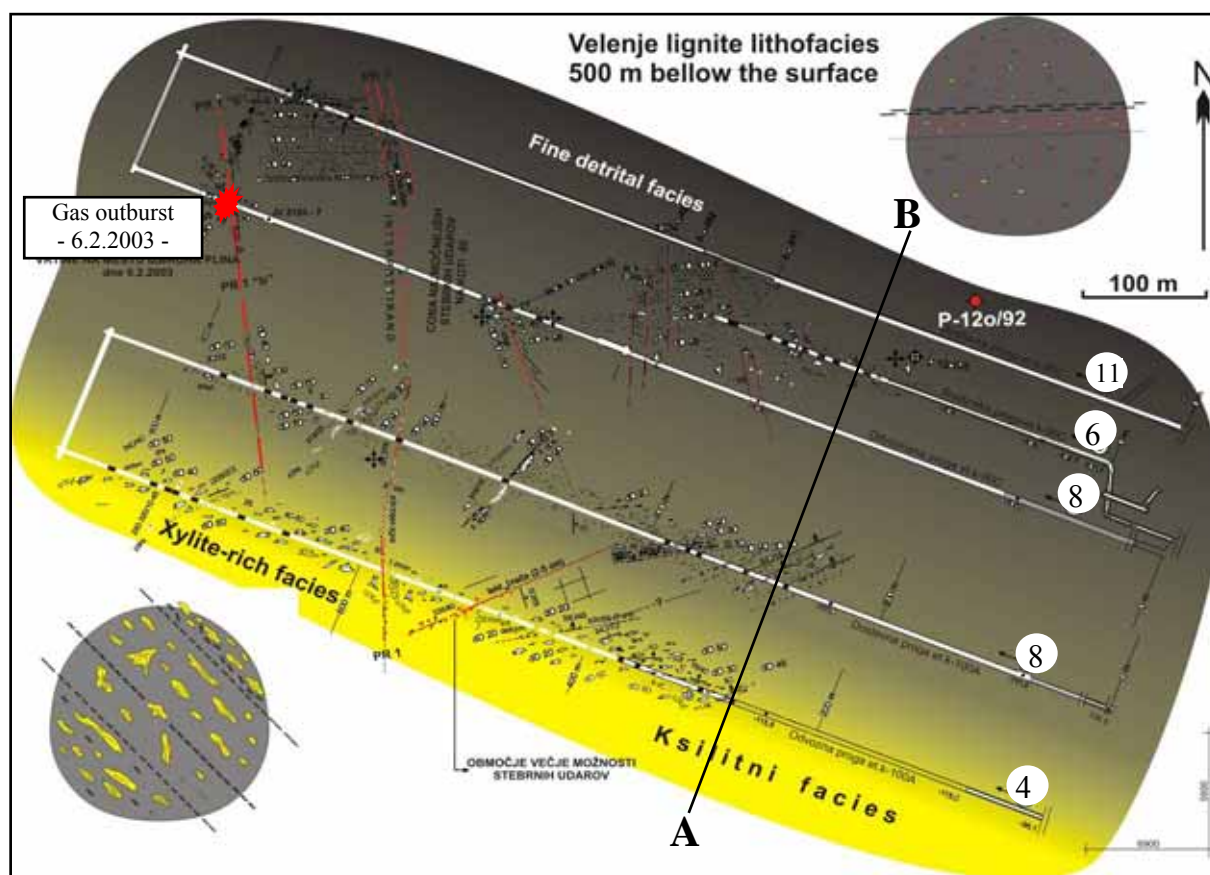


**Fig. 6.35:** Situation of the mining objects in the Preloge sector (“Jama Preloge”) separated into the southern and the northern wing. The distribution of prevalingly xylitic (and xylo-detrital) and prevalingly fine-detrital lignite facies is shown.

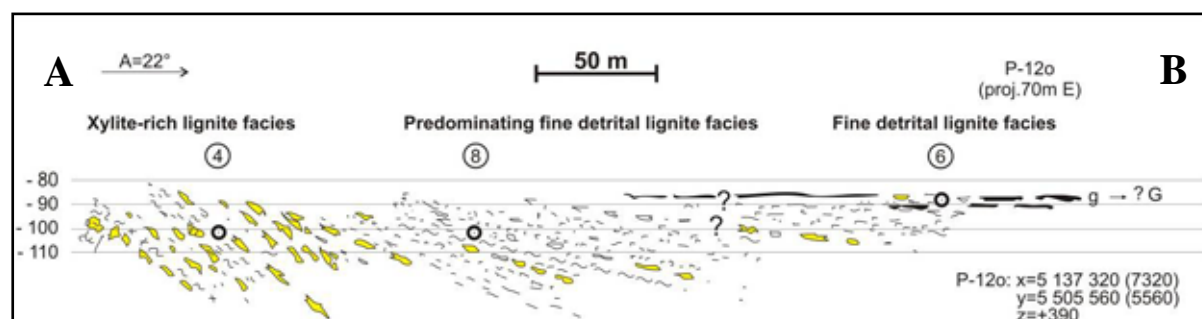
The most important result of the mapping was that the xylite-rich lignite facies clearly predominates along the periphery of the lignite seam, whereas fine-detrital lignite facies characterizes its inner part at approximately the same height level. Another finding was that the dip of the lignite gradually decreases from the periphery toward the inner part and from the bottom towards the top. Both generalities are visible from **Figs. 6.36, 6.37, and 6.38**.

**Figs. 6.36 and 6.37** show the distribution of lignite facies as interpreted on the basis of mapping of the mining roads and the long-walls at levels -90 and -100. Similarly, **Fig. 6.38** shows the results of mapping of analogous mining objects approximately 10 m below the previously mentioned objects. In **Fig. 6.36**, at the bottom-left and top-right, two typical road-faces presenting: a) considerably inclined xylite-rich strata of lignite along the southern (SSW) margin of lignite accumulation, and, b) fine-detrital lignite in the inner part of the basin, are shown. Marked is also the locality of a huge gas outburst in road “8” – level -90C. The location was “post festum” petrographically examined in detail – and is discussed separately in **Chap. 6.3.3.3.3**.

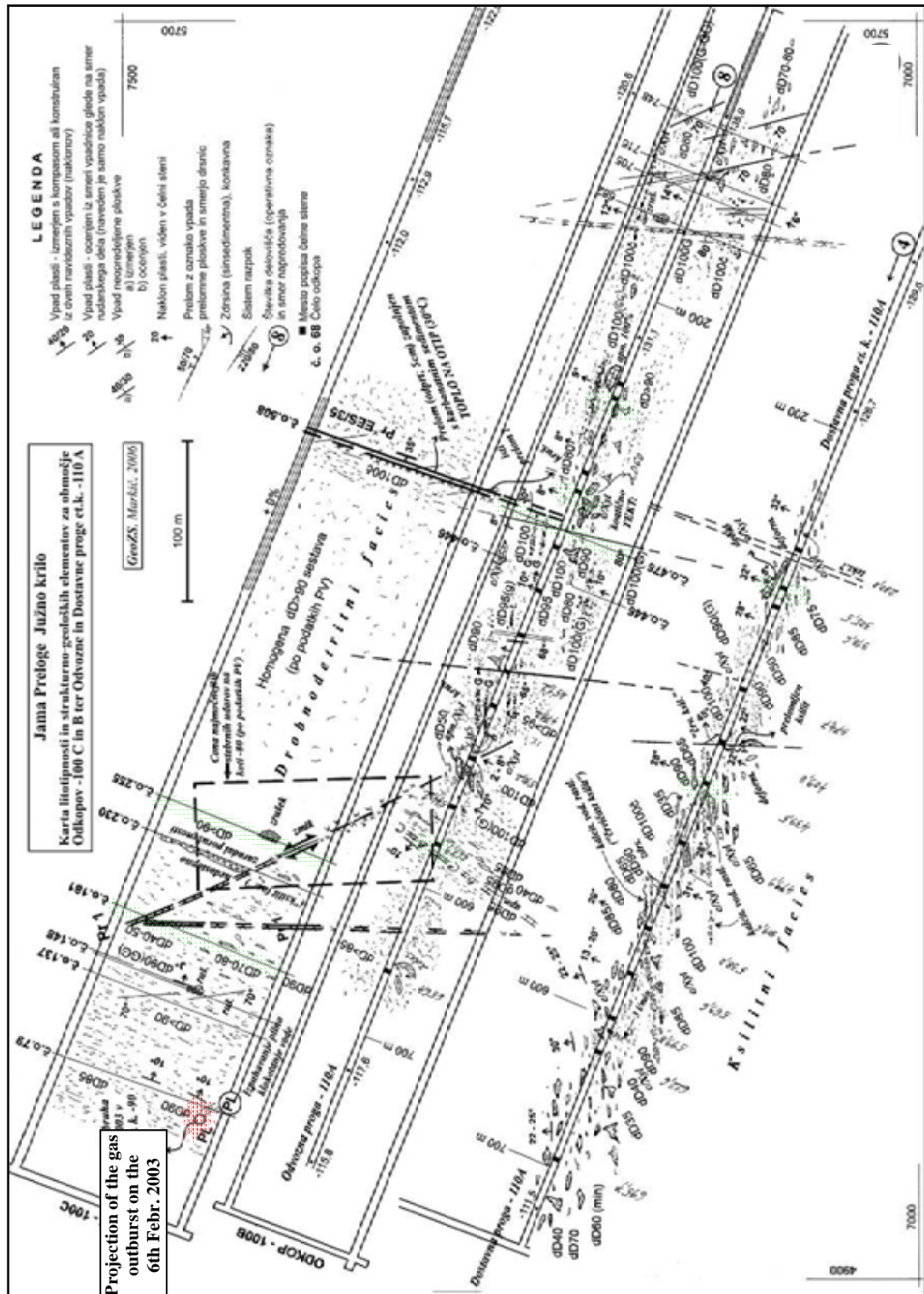




**Fig. 6.36:** Interpretation of the lignite facies distribution in the Preloge sector at levels -90 and -100. In the bottom-left and top-right corners, characteristic lignite facies as observed in the road-faces are shown: xylite-rich facies along the southern periphery, and fine-detrital facies in the central part of the lignite seam. Mining roads (abbreviated by numbers 4, 8, 8, 6, and 11) were made from ESE toward WNW (azimuth 292°). At the ends, they were connected to form long-walls which then ran back towards ESE. In road “8” (-90C), a huge gas outburst happened on the 6<sup>th</sup> of February 2003, when the long-wall was at 68 m (see also **Figs. 6.41** and **6.42**).



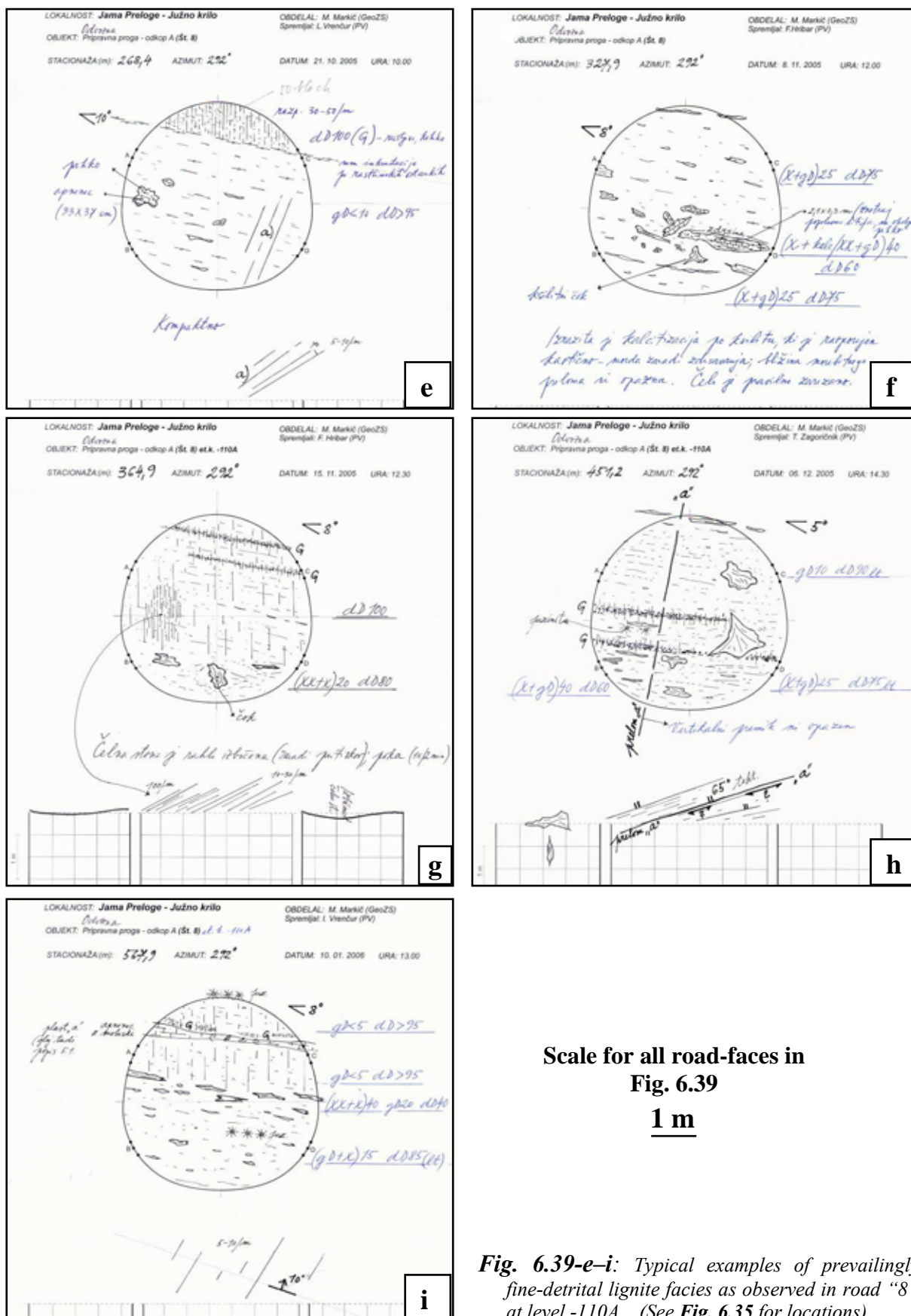
**Fig. 6.37:** Schematic A–B profile (for its location see **Fig. 6.36**). 4, 8 and 6 are the mining roads. Illustrative is a gradual decrease in dip of the lignite from the southern, xylite-rich margin of the lignite seam toward the laterally inner area of the seam composed of fine-detrital and gelified lignite.

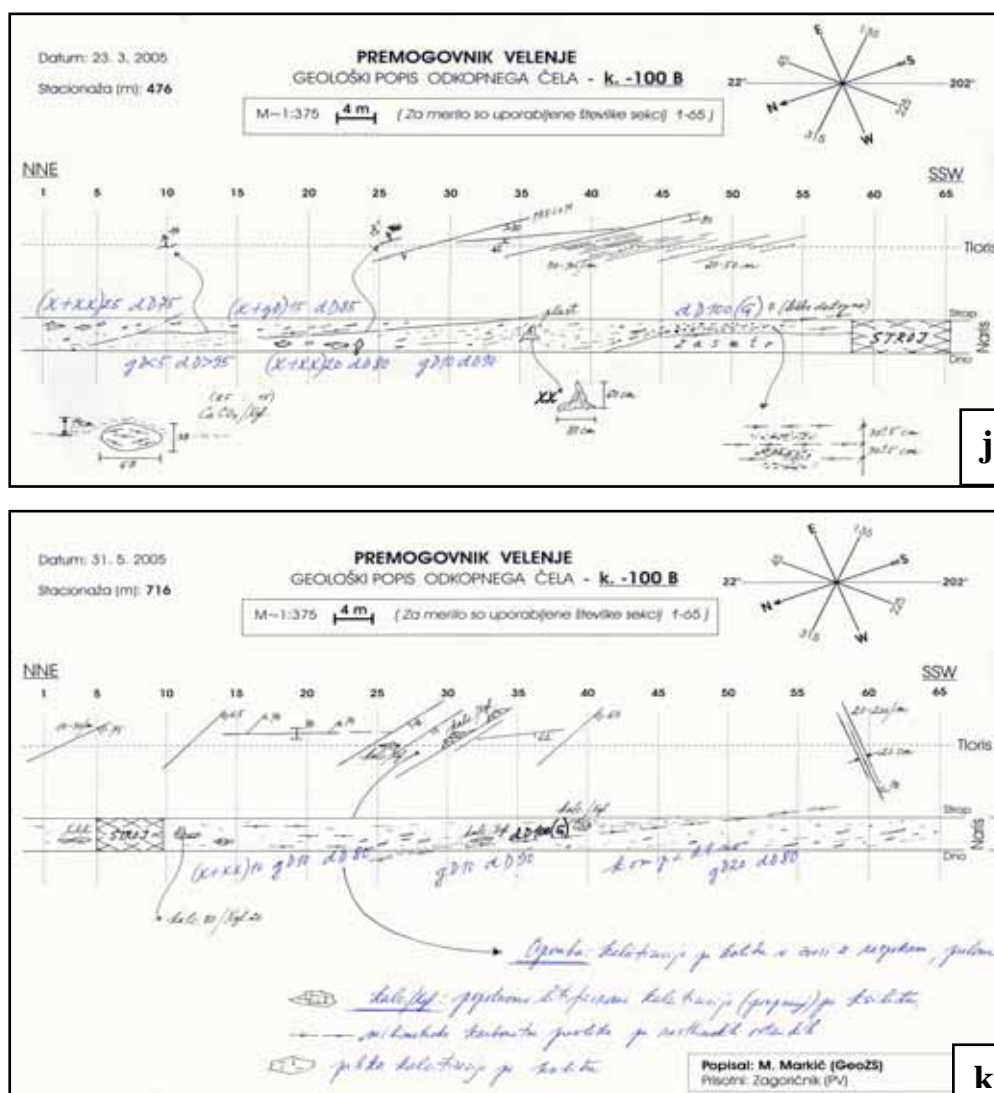


**Fig. 6.38:** Petrographic map of the Preloge southern wing area, based on data from mining objects at levels -100 and -110. Facies distribution is similar as discussed for Figs. 6.36 and 6.37. For detailed petrographic characteristics as recorded in selected road-faces and long-walls (marked by green or very pale gray in grayscale), see Figs. 6.39-a-n





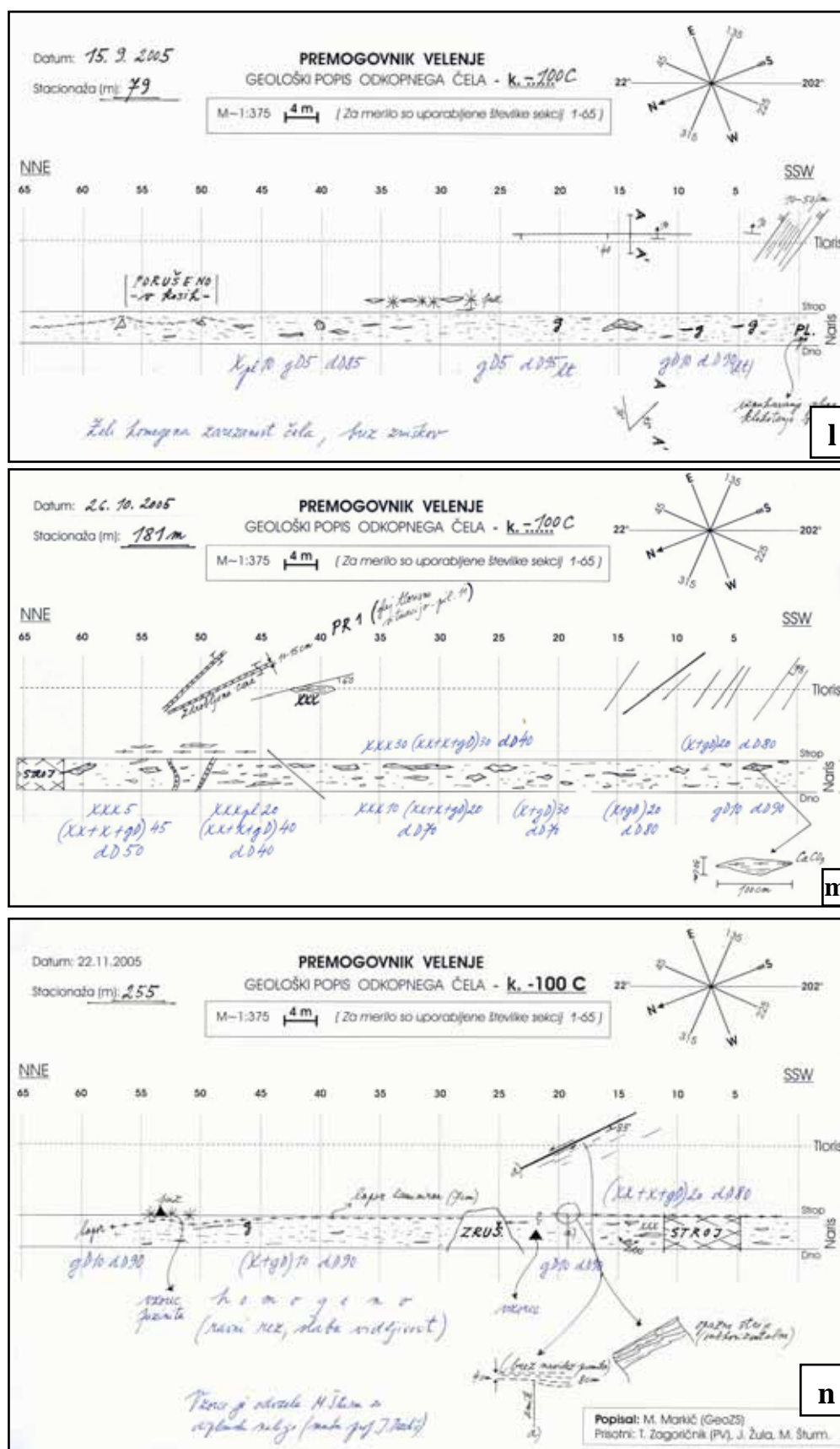




**Fig. 6.39-j,k:** Typical examples of prevalingly fine-detrital lignite facies as observed in the long-walls -100B. (See Fig. 6.35 for locations). In **j**), laminar calcification and connected gelification of fine-detrital lignite are notable on the SSW. In **k**), calcified xylite was encountered in connection with a fault fracture.

Xylite-rich lignite facies (**Figs. 6.39-a-d**) contains more than 15 % of clearly visible xylitic fragments, which can be mostly interpreted as remnants of tree and bush vegetation. Their dimensions vary from centimetre sizes (xD and dX) up to several decimetres and more (X and XX) (**Chap. 6.3.1**, and **Fig. 6.8**). Pieces bigger than one or even two metres (XX and XXX) are encountered more rarely (see e.g. road-faces at 24.0 and 36.0 m in **Fig. 6.43**). Xylites are most often platy (**Fig. 3.1-a**) and concordant to stratification, but may also be stout (**Fig. 3.1-b**), deformed, non-concordant to stratification, and chaotically distributed.

Xylite-rich environments, especially when containing heterogeneous pieces together with stumps, can be supposed as relatively oxygen-rich environments. This is due to inflowing oxygen-rich waters and also due to partial exposure of woods (xylites) to the atmosphere. Sporadically, paleo-forest and bush swamps (giving rise to xylite-rich coals) were also subjected to forest fires. The first effect, slight oxidation, often together with enhanced fungal activity, causes semi-degradofusinitization, which is visible only microscopically (**Fig. 4.9-b, c, d**), whereas another one - oxidation due to sporadic forest fires - is reflected by the occurrence of fusite (or microscopically as (pyro-)fusinite). Fusite is clearly visible with the



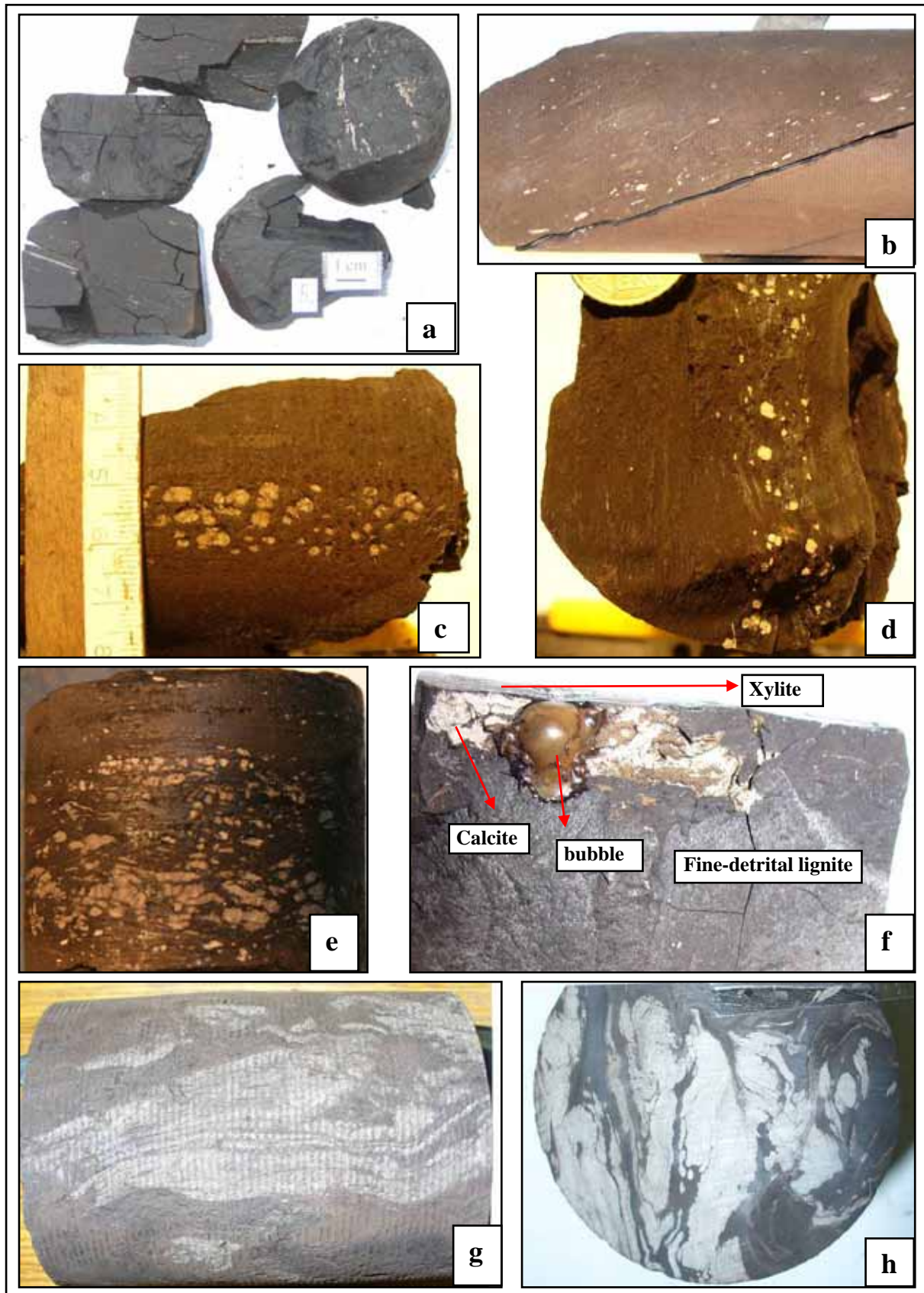
**Fig. 6.39-l:** Typical examples of prevalingly fine-detrital lignite facies as observed in the long-walls -100C. (See Fig. 6.38 for locations). In l, in the SSW, the site PL- i.e. a very close site to the gas explosion on 6<sup>th</sup> February 2003 is marked (see also Fig. 6.41).



naked eye (**Figs. 6.5 and 6.39-c, d, i, l, n** (signed by asterisks)). Fusite or charcoal occurs most often as encrustations of outer parts of xylite pieces.

The next prominent characteristic of separate, most often big pieces of xylite is **calcification**. Calcite occurs either as loose (earthy, mouldy) encrustation encompassing mainly the outer parts of xylite lumps (**Figs. 3.2-b, 6.9-c**) or as massive, lithified (“true”) limestone, either only in the interior of xylites (**Fig. 6.9-c**) or replacing the entire xylite (**Fig. 3.2-a**). The interpretation of calcification is that Ca-rich waters contacted xylitic pieces and the reaction between the released CO<sub>2</sub> from xylite and Ca from water gave rise to increased CaCO<sub>3</sub> formation. The process could be very intensive in the interior of the woods in the so called heart wood with thick tracheids (as slightly still visible in **Fig. 3.2-a**). Tracheids enabled water circulation (e.g. SWEENEY et al., 2009), but the whole system was quite closed and thus enabled the concentration of Ca and CO<sub>2</sub>, as well as “enough time” for their reaction to form calcite. HAMRLA (1952) supposed carbonate-rich muddy sediments, if deposited above the xylite horizons, to be the source of Ca. In this case, Ca could react especially to those xylite pieces which were protruding the surface of the biomass accumulation. This explanation is in agreement with our observation that calcified xylite occurs only sporadically. On the other hand, a clear relation between carbonate-rich (marl) layers and calcified xylites was not found, or, conversely, in the vicinity of the marl bands, no special accumulation of calcified xylites was encountered (e.g. **Fig. 6.39-i**). Further on, the calcification of the inner heartwoods implies the seeping of Ca-rich water from the substratum rather than from the topstratum. Quite characteristically, the calcification appears in chaotically distributed lumps as in **Fig. 6.39-f**. From some of these aspects it is ambiguous whether the calcification of big xylitic pieces is always syngenetic (as suggested by HAMRLA, 1952). In fact, the connection between calcified xylites and prominent fracture zones (first pointed out by M. VRABEC; pers. comm.), which may have formed pathways for Ca-rich waters, suggests an epigenetic origin (see also **Fig. 6.39-k**). But, controversially to the statement of “epigenesis”, calcite mineralization was not observed to occur in the fractures (cleats and joints) within the lignite, neither macro- nor microscopically. Some preliminary C and O isotope investigations of calcified pieces were performed by T. KANDUČ (pers. comm.), but did not clarify this question.

Another form of calcification represents replacements, sometimes only encrustations, of small, millimetre to centimetre sized plant particles. In road-faces and long-walls, where the lignite is observed from a greater distance, this type of calcification is often visible as very regular lamination and is undoubtedly syngenetic. It is observed in fine-detrital lignite and may represent contacts between lignite layers of somewhat different composition but mostly within fine-detrital lignite facies. Typical examples of such lamination, which can consist of only one lamina or of several laminae but mostly not exceeding in a whole a package of 5–10 cm, are presented in **Figs. 6.39-e,j,k**. The formation of this type of calcification can be again explained by the fixation of Ca from percolating water at the water/fine-detrital organic sediment/atmosphere boundary. The release of CO<sub>2</sub> from plant remains, mixing of fresh and more saline water, changes in partial pressure and temperature, all these seasonally alternating factors, can balance carbonate precipitation. Beside laminar calcification, this form may also occur less regularly, occupying only separate particles, clusters of particles etc. Some examples of different types of calcification described above are presented in **Fig. 6.40**.

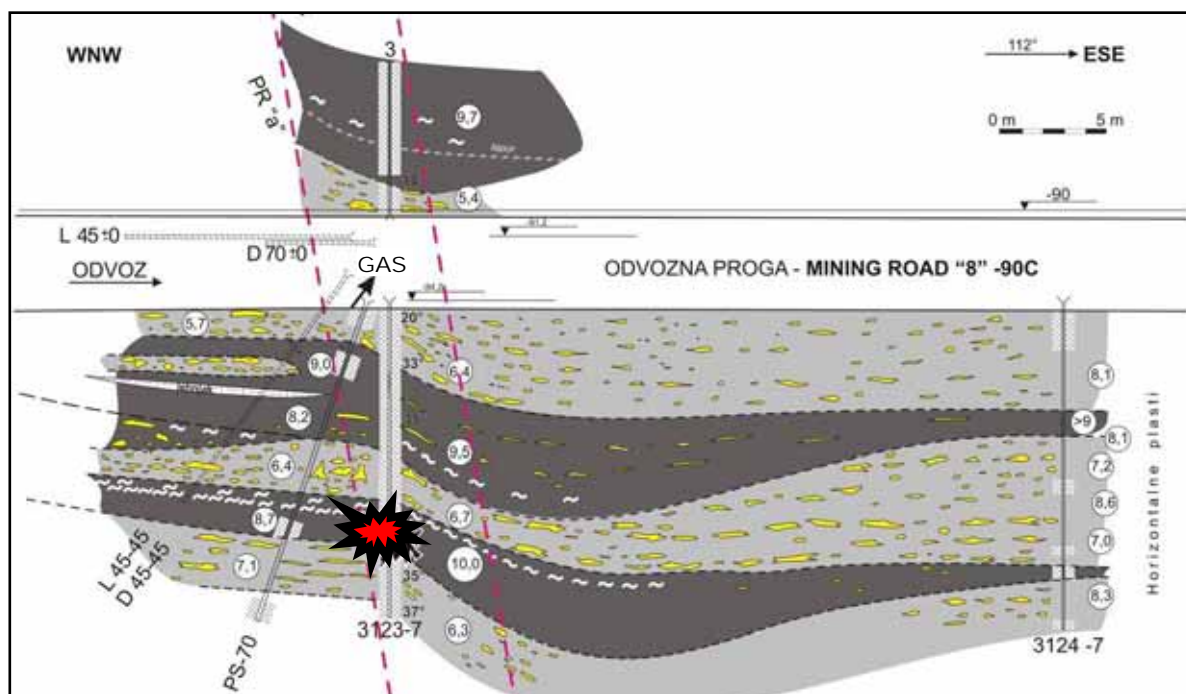


**Fig. 6.40:** Different types of calcification of plant remains of different sizes – from very small in photos **a)** and **b)** to the large ones in photos **g)** and **h)** (examples are from borehole-cores, ca. 6 cm in diameter). For calcification into “true” limestone see also **Figs. 3.2** and **6.9**. A bubble in photo **f)** is due to reaction between calcite and diluted HCl acid.)

Fine-detrital lignite facies (**Figs. 6.39-e-n**) contains less than 15 % of xylitic fragments. If still brown in colour, it contains thin fibrous xylitic inclusions. Such fine-detrital lignite is tough and hence geomechanically advantageous. As seen from **Figs. 6.39-e-n**, separate beds of fine-detrital lignite mostly do not exceed a thickness of four meters. Black homogeneous variety of fine-detrital lignite does not include xylitic fragments. Sharp edges, a dense cleat pattern, fragility, and conchoidal fracture indicate a considerable degree of gelification of this type of lignite. Cleat spacing in gelified lignite (**Figs. 6.39-e,g,i**) is only 1–3 cm. Strongly gelified lignite occurs mostly in thin beds. In **Fig. 6.39-e**, the two detrital lignite beds (dD100 and dD>95) are separated by a thin lamina-set of calcite incrustations. In **Fig. 6.39-i**, gelified lignite directly overlies a limestone/marl band with molluscs. Even better examples of this connection are in **Fig. 6.31** at positions 98.5 and 110.0 m and in **Fig. 6.43** at positions 24.0, 36.0, 55.5, and 82.5 m.

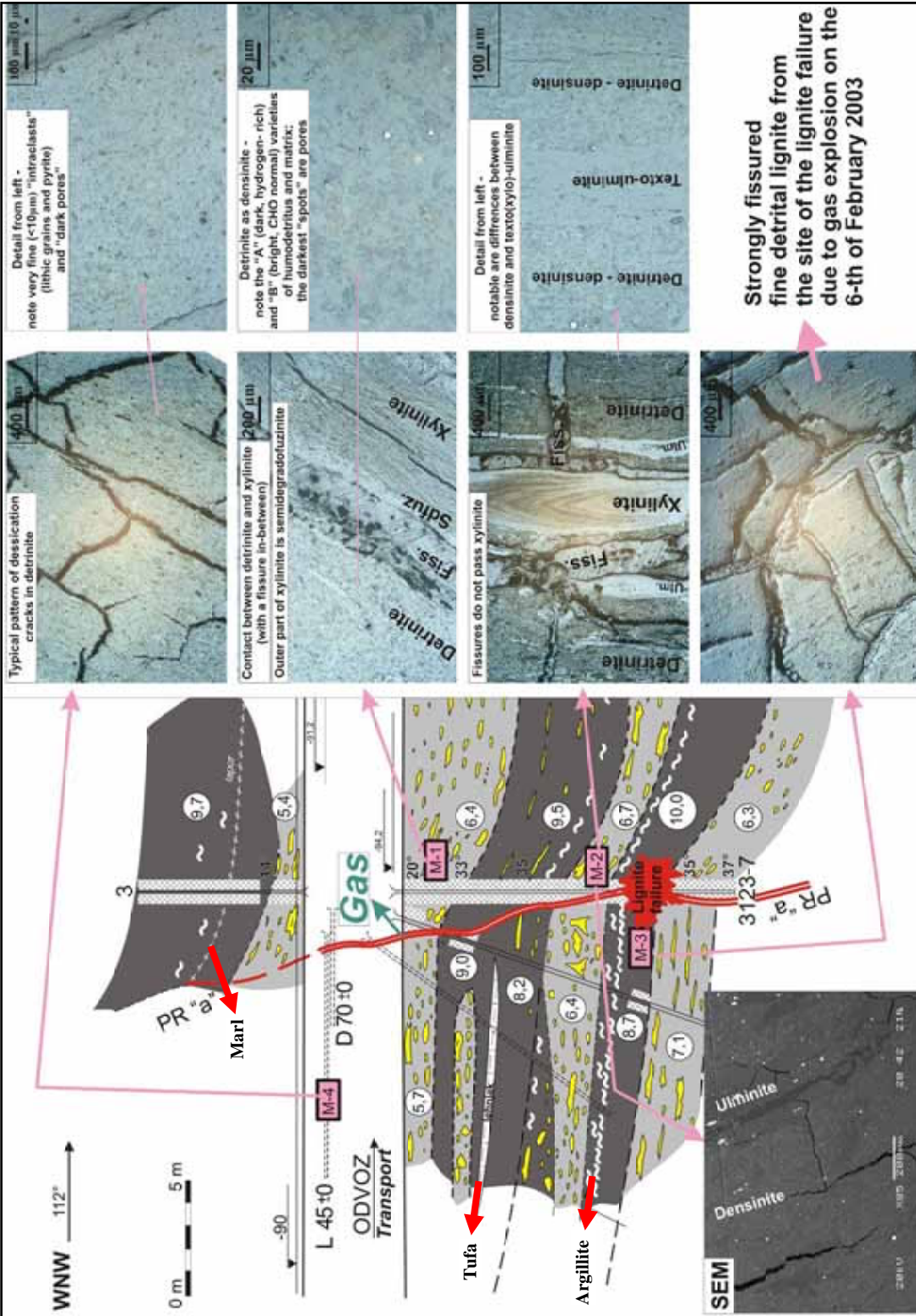
#### 6.3.3.3.3. Location of the gas outburst in the road »8« at the level -90C on the 6<sup>th</sup> of February 2003 (southern wing of the Preloge sector)

On the 6<sup>th</sup> of February 2003, a huge gas outburst happened in the mining road “8”, level -90C (**Figs. 6.36**). Immediately after that, the location of this event was thoroughly investigated by petrographic core logging of 10 boreholes in a total length of 134 m. The macro-petrographic interpretation is presented in **Fig. 6.41**, whereas some micro-petrographic peculiarities are presented in **Fig. 6.42**. The source site of the gas release as localized due to lignite failure and seismic shock by the seismographs installed at the mine was ca. 11 m below the floor of the road. It was proved that the hosting lignite was the fine-detrital one, also slightly gelified, coded by value 10. The borehole-cores were mostly strongly crushed.



**Fig. 6.41:** Macro-petrographic interpretation of the gas-outburst locality in road »8« at level -90C which happened on the 6<sup>th</sup> of February 2003. The alternation of fine-detrital and xylite-rich lignite beds (petrographic composition expressed in code values) is evident. Marked (with a banner) is the source site of the gas release about 11 m below the road floor. In this figure, the deformation of strata is interpreted as a flexure zone. Notable are clayey, tufa and marl intrabeds within the fine-detrital lignite facies.





**Fig. 6.42:** Macro-petrographic interpretation on the left is copied from **Fig. 6.41**. Deformation of strata is interpreted by a fault (plus a flexure zone). On the right, micro-petrographic peculiarities (optical microscopy in reflected light in air) are presented. In the lower left, a scanning electron microscope (SEM) image is added. (The term xylinite is used – instead of telinite – to point out the fossil wood (xylite) origin of this maceral).

Two and a half years later, in September 2005, the source site of the gas outburst (see “lignite failure” in the red callout in **Fig. 6.42**) was reached by the long-wall (at 79 m – **Fig. 6.38**) shown in **Fig. 6.39-l**. As seen from **Fig. 6.39-l**, the whole long-wall ran within fine-detrital lignite, with no extraordinary specifics other than somewhat more pronounced gelification in separate thin intrabeds and a relatively pronounced fracture system (10–50/m i.e. 2–10 cm apart) running in the NW-SE direction. This situation corresponds well to the borehole-based petrographic interpretation as shown in **Fig. 6.41**. As seen from **Fig. 6.41**, the lignite beds do not consist of only fine-detrital lignite but also of the xylite-rich one. Both facies are alternating. This fact seems to be somewhat contradictory in respect to the previously frequently mentioned statement, based on the mapping of the road-faces and long-walls that fine-detrital lignite highly predominates in the inner part of the lignite seam in the Preloge sector. The contradiction, at least to some degree, originates from different data sets, namely from borehole-core logs and from mining objects. Data of the first kind are more detailed, but restricted by the core dimensions (xylite “is everything xylitic extending over the dimensions of the core”), whereas those from mining objects are more general. As well, in fact, in the mining objects not only fine-detrital but also xylite-rich facies was encountered in some places (e.g. **Fig 6.39-m**).

Within the fine-detrital facies at the gas-outburst locality, thin but outstanding intra-beds of argillite, a tufa-like sediment, and marl were found (**Fig. 6.42**). At the source site of the gas release (marked red), the thin clayey layer probably acted as a seal above the gas accumulation.

As seen from strata deformation in **Figs. 6.41** and **6.42**, tectonic phenomena played the most decisive role also in this outburst, as mostly known from the former similar events as well.

#### 6.3.3.3.4. G1/D and G2/A roads in the northern wing of the Preloge sector

Petrographic interpretations of the G1/D (**Fig. 6.43**) and the G2/A (**Fig. 6.44**) roads are considered representative for the northern wing of the Preloge sector. Locations of the two roads are visible from **Fig. 6.35**. The approximately parallel roads ran from SW to NE, ca 350 m apart, moderately upwards (+9° and +5°), and both in the upper part of the lignite seam about 15 to 20 m below the clayey roof strata (or so called lignite/hanging-wall contact).

In road G1/D, the first four road-faces at 24.0, 36.0, 55.5, and 82.5 m (**Fig. 6.43**) are especially interesting. In all these cases, the relation between the marl intrabed and the surrounding fine-detrital lignite is especially notable. The latter is clearly gelified, even more, it is strongly gelified at the direct contact to the marl band, both above and below, whereas the intensity of gelification decreases away of the carbonate bed. This is, once again, a clear evidence of influence of alkaline geochemical environment (due to carbonate presence) on an enhanced gelification process affecting most easily fine-detrital biomass. Large wood remains, 2–3 m long and 0.5 – 1 m wide (thick) were encountered above the marl layer. In spite of carbonate presence, they do not show any calcification. A large lump of xylite at position 36.0 m in **Fig. 6.43** (visible on the right side of the road-face), which slid into the fine-detrital peat, is very illustrative. In general, as visible from the rest of the road-faces, the G1/D road ran through xylitic lignite with 20–45 % of xylitic dXxD, X, and XX components.





**Fig. 6.44:** Petrographic interpretation of road G2/A in the northern wing of the Preloge sector. Xylite-rich versus fine-detrital lignite facies are clearly distinguished on the basis of both road-face mapping and borehole-core logging. In the (low-ash) fine-detrital lignite bed, increased natural radioactivity was detected.

The prevailing petrographic type of lignite in the G2/A road (**Fig. 6.44**) is similar as in the previously described G1/D road (**Fig. 6.43**), i.e. the xylite-rich one with 20–40 % of xylitic dXxD, X, and XX components. However, in the lower part of this road, a fine-detrital lignite bed was also detected both by road-face mapping and by two cored boreholes, JH-2 and JH-3. In the mentioned boreholes, from the year 2006, a set of geophysical measurements was carried out by the company Brunnen-und Bohrlochinspektion GmbH (Bbi, MAURER et al., 2008) and numerous types of petrophysical investigations on the lignite core-samples were led by Professor Andreas WELLER from the Technical University in Clausthal (NORDSIEK & WELLER, 2008). These investigations were later expanded to additional three boreholes in 2007 and 2008. They were focused on answering the question whether it is possible to distinguish between different petrographic types of lignite on the basis of measurable physical or structural properties. The study is still in course and will not be debated here more in detail. Only two interesting preliminary results will be mentioned. The first result is an outstandingly increased total natural gamma radioactivity of the fine-detrital lignite bed (by natural gamma ray log) (MAURER et al., 2008). It seems that this effect could help in strata distinguishing. The mentioned fine-detrital lignite in the G2/A road and the JH-2 and JH-3 boreholes, respectively, was a “clean” variety with no special mineral admixtures. Namely, in the most recent borehole, JV-3374-T/08, an increased radioactivity was also detected in the mineral-rich fine-detrital lignite (MAURER, personal comm.). The second result was the correlation between the magnetic susceptibility and the lithotype variety of lignite (NORDSIEK & WELLER, 2008). Magnetic susceptibility of the xylite-rich samples ranges between  $-4$  to  $-6 \times 10^{-6}$  SI units, whereas that of fine-detrital lignite samples between  $-2$  to  $+4 \times 10^{-6}$  SI units.

#### **6.4. Micro-petrographic characterization of the Velenje lignite – mostly based on the maceral analysis of lignite in borehole-cores P-9k/92 and P-8z/92**

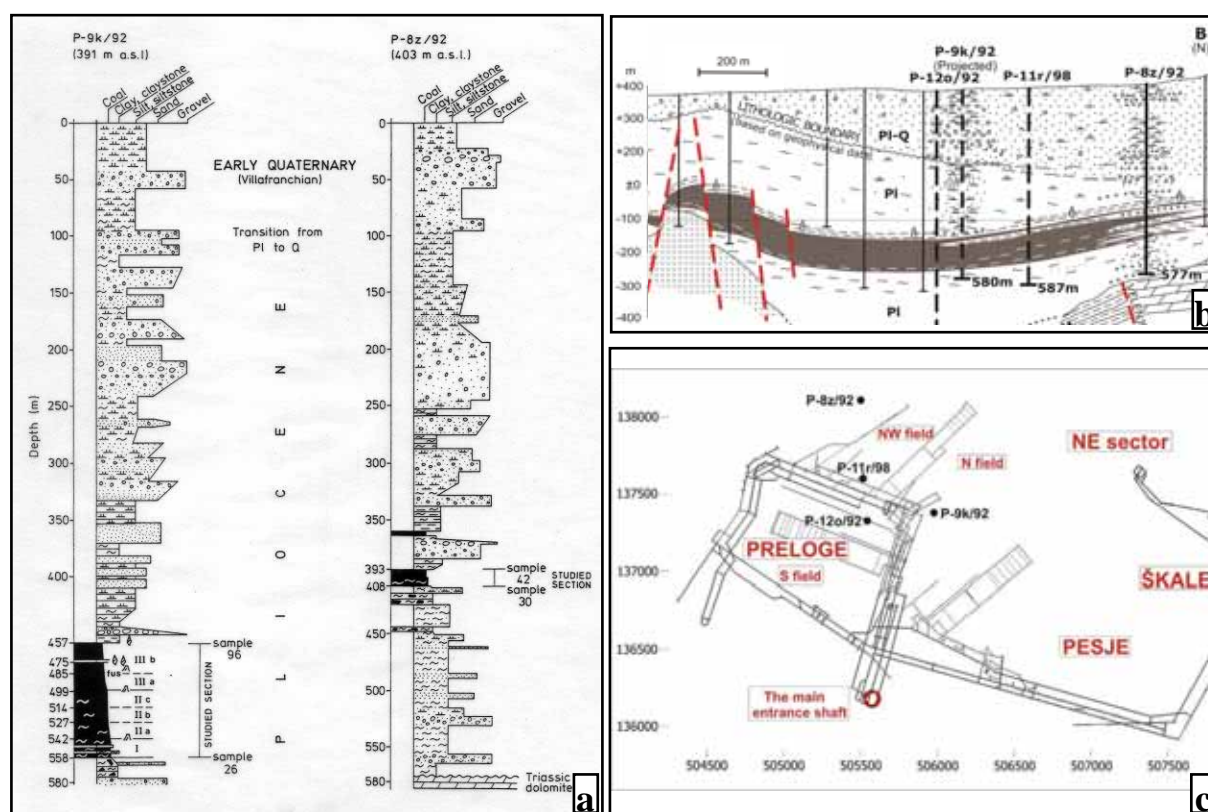
In 1990, a new polarising microscope for reflected light microscopy was purchased and installed at the Geological Survey in Ljubljana. The microscope enabled then a bloom of petrographic analyses, including coal analyses. The first huge project on coal petrography was done in the frame of geochemical and palynological study of two profiles of the Zasavje (Trbovlje) coal (UHAN, 1991, MARKIČ et al., 1993), the results of which were later incorporated also into the biomarker and isotopic characterization of this coal by BECHTEL et al. (2004).

After 1990, first micro-petrographic examinations of the Velenje lignite samples were carried out in 1993 and 1994 (MARKIČ, 1995) mainly with the aim to test whether microscopic characterization can help in solving some special geo-mechanical questions. Later, from 1997 to 1999, similar investigations were done on a set of samples referring to study adsorption and desorption properties of separate lignite varieties (ZAPUŠEK & HOČEVAR, 1998; PEZDIČ et al., 1999). More recently, scanning electron microscopy (SEM) has been introduced as an additional method to the optical microscopy. Separate micro-petrographical inspections have also been performed recently in order to clarify some specific petrophysical properties. However, all these investigations and accompanying results will not be discussed here, because they were mostly carried out only as a “petrographic service” to the mentioned branches of the lignite examinations. Our further debate will be thus concentrated on a systematic micro-petrographic analysis of lignite profiles in boreholes P-9k/92 and P-8z/92.

### 6.4.1. Petrographic analysis of lignite in boreholes P-9k/92 and P-8z/92

Micro-petrographic study of the Velenje lignite on the core profiles of boreholes P-9k/92 and P-8z/92 was carried out during the first author's three-month study-visit to the Institute for Geosciences – Mining University Leoben in Austria. The results, including the interpretation of depositional environments of the Velenje lignite seam formation were published two years later by MARKIČ & SACHSENHOFER (1997).

For borehole positions, the reader is referred to **Figs. 2.2, 2.4, and 6.2**. Lithologic columns of the boreholes are given here in **Fig. 6.45**, while the lignite seam analysis in terms of lithotypes following the ICCP classification concept (**Tab. 6.1**) was already presented in detail in **Figs. 6.22 and 6.23**. In **Fig. 6.46**, lithotype variability throughout the seam in the two profiles is presented once again, this time as a lithotype curve. Because megascopic logging of the two boreholes represents a basis for further petrographic study, this will be described first.



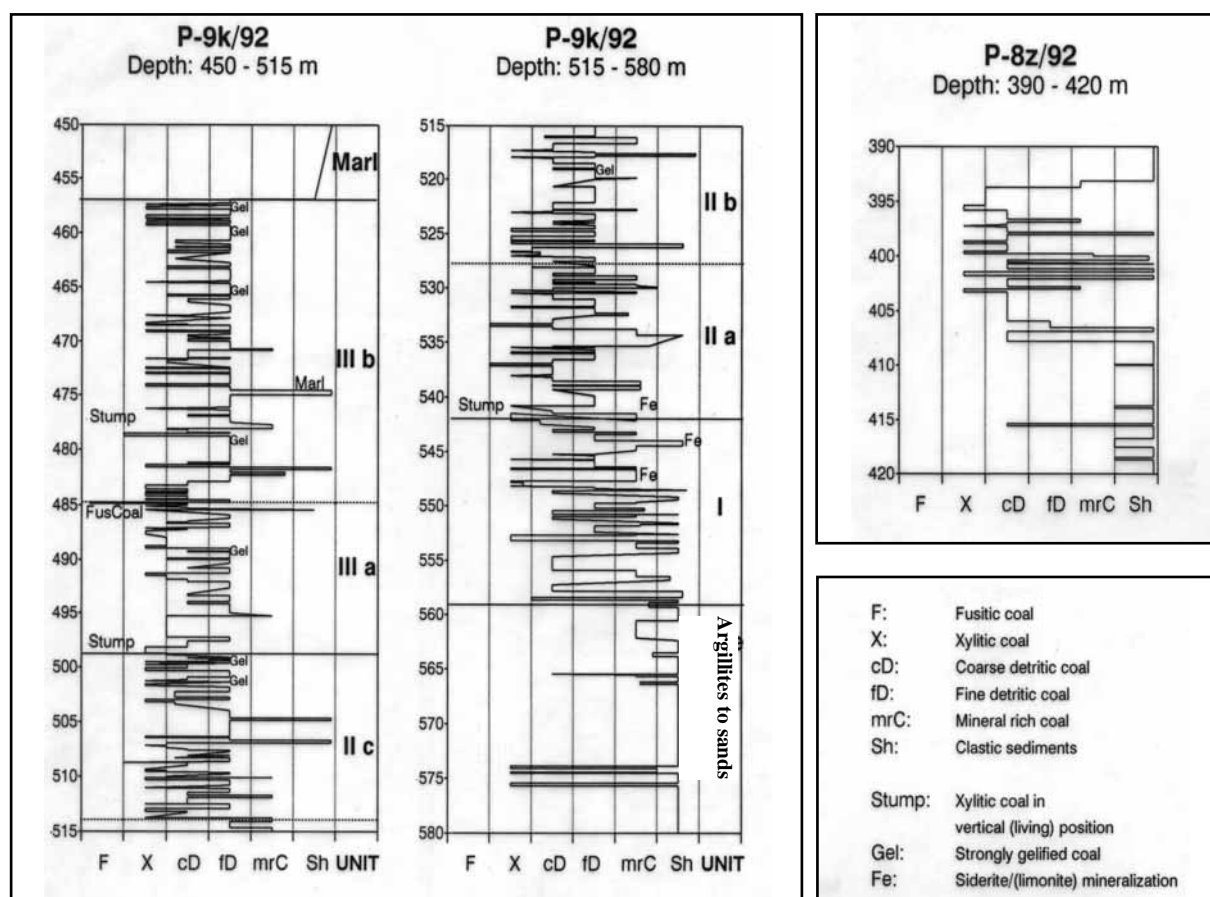
**Fig. 6.45:** a) Lithology and chronostratigraphy of the sedimentary sequence drilled-through by boreholes P-9k/92 and P-8z/92. b) and c) Positions of boreholes P-9k/92 and P-8z/92 in the general basin profile and in the plan-view map.

#### 6.4.1.1. Megascopic description of lignite in boreholes P-9k/92 and P-8z/92

As summarized from the macroscopic study of both boreholes (**Figs. 6.22 and 6.23**), the lignite accumulation in the central part of the basin (P-9k) grades from ash-rich lignite at the bottom to increasingly higher grade lignite at the middle and the top of the seam. Along the northern margin (P-8z), the lignite accumulation is thinner, divided into several more or less

ash-rich lignite splits. Fluvial to marshy sediments, fining upwards, form the floor of the lignite seam in both the central and the northern marginal part of the basin (**Fig. 6.45**; see also **Fig 2.3**). At the top, in both cases, the lignite is sharply contacted to the lacustrine marl bed with molluscs. The continuation of the sedimentary fill above the lignite seam consists of alternating fluvio-lacustrine sediments of different grain sizes, composition, degree of lithification and other lithologic features. The share of coarse-grained sediments is higher in the northern part of the basin than in the central part. Interestingly, at the P-8z locality, gravel occurs even within the lignite horizon at its upper part. All these features correspond well to the “BREZIGAR's (1981) alluvial fan”, which prograded into the basin from the north to the south.

The lignite in borehole P-9k/92 represents, due to its central position in the basin and also due to its thickness, a representative lignite profile in the Velenje basin. After basic logging, the second step was an attempt to subdivide the lignite seam at this location into petrographically distinctive units and/or subunits. Petrographic distinction between the lower, the middle, and the upper part of the lignite seam was quite easily made at the very beginning. The mentioned parts of the lignite seam were thus designated (upwards) as units I, II, and III (**Fig. 6.46**). Unit II was further-on divided into subunits II-a, II-b, and II-c, whereas unit III into subunits III-a and III-b.



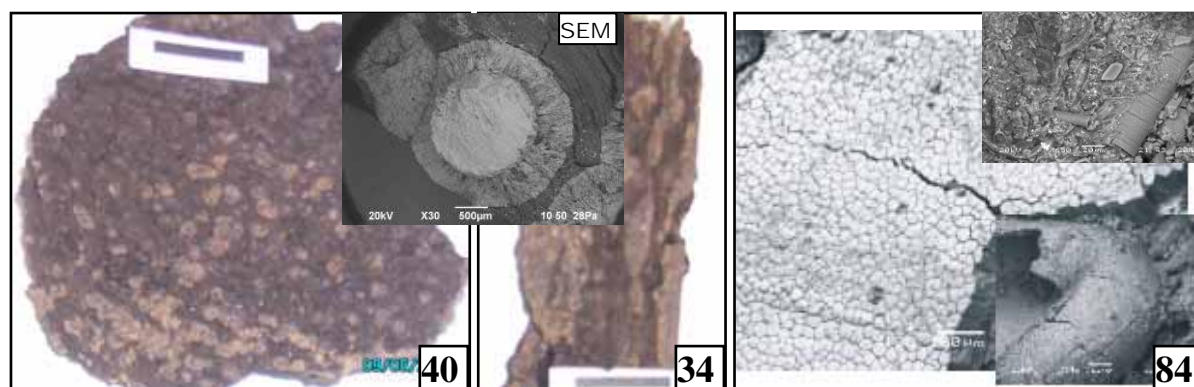
**Fig. 6.46:** Petrographic logs of the lignite seam drilled and cored by the P-9/92 and P-8z/92 boreholes. Lithotype variability is expressed by a lithotype curve. Coarse detritic coal (cD) is an older expression for xylo-detrital (dXxD) coal (from MARKIČ & SACHSENHOFER, 1997). For the source petrographic logs see also **Figs. 6.22 and 6.23**.



Internal bedding within the lignite seam can be regarded in a basic sedimentological sense, which says that the “bedding is produced mostly by changes in the pattern of sedimentation, usually changes in sediment composition and/or grain size” (from TUCKER, 2001, p.25). Lignite beds can be thus defined as layered bodies, which are thicker than 1 cm and exhibit an outstanding lithotype composition and texture. A separate lignite bed must be clearly distinguished from the adjacent beds. Bounding planes (also termed bedding surfaces or bedding planes) should be clearly visible, if speaking about true bedding. If not – and this is quite frequent in the case of coals – the term “banding” is well known in coal petrography (especially for hard coals). If the layered bodies are thinner than 1 cm they are termed laminae. Beds can be internally layered, whereas laminae are internally uniform (except in special cases for some gradational features).

When studying lignite in borehole-cores, due to restricted dimensions of observation, bedding cannot always be exactly and clearly determined. A better insight into the bedding texture is gained in observations of larger lignite surfaces as already presented in previous chapters for road-faces and long-walls. In borehole log P-9k/92, petrographically distinctive intervals are mostly less than 1.3 m thick. Thicker uniform intervals occur only sporadically. A great majority of separated intervals is less than 0.6 m thick. The lowest logging thickness of a separate petrographically distinctive interval was 5 cm.

**Unit I** in lignite profile P-9k/92 is characterized by mineral-rich lignite with clayey partings. An average ash yield of this unit reaches nearly 35 % at the dry basis (*db*) (including partings; for the ash yield data see **Tab. 6.14**, **Tab. 7.1**, and **Fig. 6.60**). In the organic part of lignite, xylodetrital and xylitic lignite predominates over fine-detrital one. A similar relation will also be true for the above lying subunit II-a. Characteristic for the lowermost part of the seam is Fe mineralization, mostly as spheroidal siderite and limonite replacements over woody tissues (**Fig. 6.47**).



**Fig. 6.47:** Samples 40 and 34 from borehole P-9k/92 are iron-rich (scale bar is 1 cm). Fe occurs in concretions (SEM image) composed of siderite (centre) and limonite (periphery). Sample 84 (SEM image) is a marl sample with gastropods from the same borehole (see **Fig. 8.3** for the position of the samples).

**Unit II** represents the transition between units I and III. As a criterion for fixing the boundaries between the mentioned units at 542 m and at 499 m depths, prominent stump horizons, characterized by large xylites in a close-to-vertical or growth position (see also **Fig. 6.22**), were taken into account. The lowermost part of unit II, i.e. the II-a, still resembles unit I, whereas subunits II-b and II-c already resemble the upper unit III. Subunit II-a quite clearly shows an environmental shift from more waterlogged to more oxidative conditions, the first



extremely characterized by many clayey partings (and absence of fusitic coal), whereas the second by almost absence of dirty partings, a lower content of mineral-rich lignite, and by sporadic occurrences of fusitic coal. Similarly as in unit I, xylo-detrital and xylitic lignite is very characteristic for the subunit II-a as well. Ash yield in subunit II-a averages to 27 % (*db*). Unit I and subunit II-a, which are both characterized by xylite and xylo-detrital lignite, can be both interpreted as originating from forest swamps, unit I from relatively wet forest swamp, and subunit II-a from a somewhat dryer forest swamp.

In units II-b and II-c, mineral-rich lignite partings are very rare. The lignite is xylo-detrital and fine-detrital with relatively frequent xylitic inclusions, especially in subunit II-c. More pronounced gelification of fine-detrital lignite was observed at some places. Average ash yield in subunits II-b and II-c falls to 20 % and less. The increased content of fine-detrital lignite in comparison to the underlying strata indicates a decrease in tree density and/or the establishment of more frequent and larger bush moor environments.

**Unit III** is characterized by a still somewhat higher portion of fine-detrital matrix versus xylitic components than in the unit II. Fine-detrital layers of lignite are also somewhat thicker than in the lower part of the lignite seam. The lignite from this unit is of the best quality regarding the ash yield, which is less variable and averages to “only” 12.5 %. Only three mineral-rich lignite intra-beds, one clayey bed and one marly layer were encountered macroscopically in unit III. The most outstanding is the marl bed at ca. 475 m depth, being ca. 0.6 m thick, and containing gastropods (**Fig. 6.47** – sample 84). The next outstanding feature of this uppermost part of the lignite is gelification. It is distinguished not entirely throughout this uppermost part of the seam but only in separate beds of fine-detrital lignite, expressed by homogeneity, almost black colour, conchoidal fracture and a high cleat density. However, also in this unit, the fine-detrital lignite of darkish brown colour is still predominant.

The predominance of the fine-detrital lignite, relatively strongly gelified in separate bands in the upper part (unit III) of the lignite seam in borehole P-9k/92 (**Figs. 6.22** and **6.46**), corresponds well to the already stated conclusion derived from the mapping of the mine workings in the Preloge sector (**Chap. 6.3.3.3.2.** and **Figs. 6.36, 6.37, and 6.38**), namely, that in the central and in the upper part of the lignite basin the predominance of fine-detrital lignite facies is quite characteristic. Mapping of underground mine workings was not carried out in the lowermost part of the seam in the central basin area. However, the predominance of xylite-rich lithotypes in the southern peripheral part of the basin and the inclination of the strata as presented in **Fig. 6.37** indicate that the marginal xylite-rich lignite facies extends into the central basin where it forms the lower and older part of the seam. This relation suggests that the southern xylite-rich peripheral part of the basin was formed in a forest mire, whereas the more waterlogged central part was formed in a wetter swamp with herbaceous vegetation. A vegetal distribution characterized by outer relatively dry forests and inner, wetter swamps with open-water surfaces is observed in many modern peatlands as well. In the case of the Velenje peat-forming setting, environments of open-water surfaces took increasingly enlarging dimensions with time, which explains why the fine-detrital facies takes grater and thicker dimensions toward the top of the seam and toward its central part.

The macro-petrography of borehole P-8z/92 in the depth interval from 390 to 420 m (**Fig. 6.46** – upper right) is characterized by clayey to sandy sediments from 420 up to ca. 408 m depth. The above-lying lignite split between 408 and 393 m depth is composed of xylitic and xylo-detrital lignite, and of clayey bands, especially in the middle of this split. This lignite split is than overlain by silty clay and by fluvial sandy gravel (see the column of the borehole

P-8z and the cross-section through the basin in **Fig. 6.45**). The high predominance of xylitic and xylo-detrital lignite in the northern, alluvial fan influenced area can be explained by forest tree vegetation which could grow in a relatively high-energy environment. Neither significant peat accumulation nor the formation of fine-detrital biomass could find place in such an environment. Most probably a part of primary tree biomass was transported into the calmer and somewhat deeper parts of the swamp as well.

#### **6.4.1.2. Core sampling, preparation of polished blocks, and microscopic method**

The sampling of both cores was aimed to carry out a quantitative micro-petrographical analysis of the lignite (*sensu* STACH et al. 1982, p. 306–311). Lignite cores of both boreholes were sampled according to the lithotype variability. 67 continuous core samples were taken from borehole P-9k/92, and 13 samples were taken from borehole P-8z/92 (**Figs. 6.22 and 6.23**). The core samples were from 0.5 to 2.3 m long. At the site of borehole P-9k/92 (central part of the basin), the sampled lignite seam was more than 100 m thick in the depth between 457 and 558 m. At the site of borehole P-8z/92 (northern margin of the basin), the lignite sampled was only 15 m thick. For the macro-petrographic analysis one half of the core was sampled, whereas the other half was archived for additional analyses.

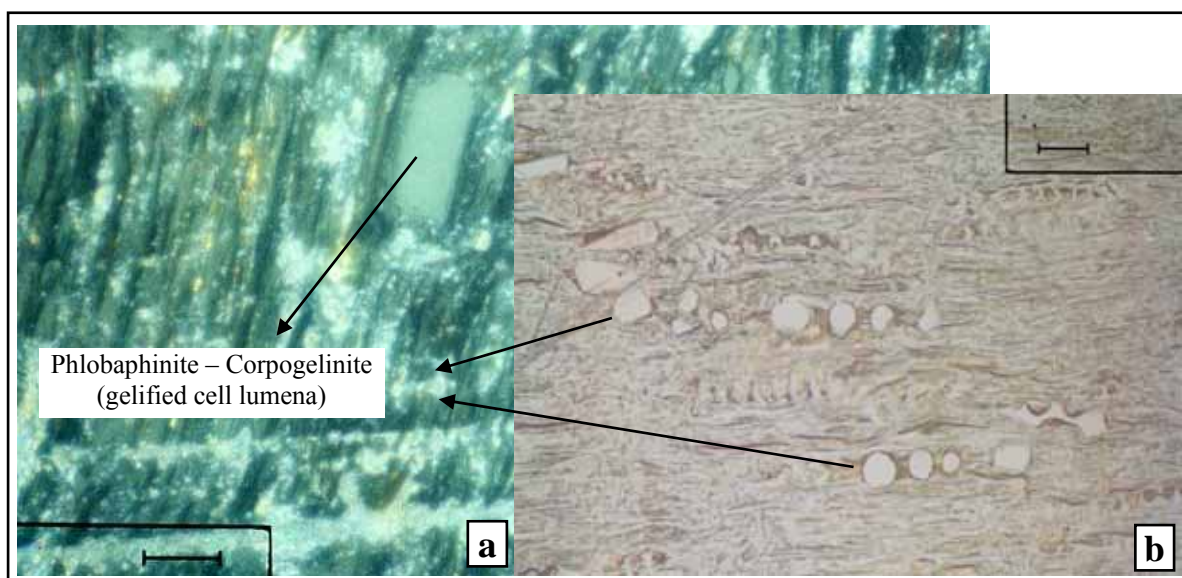
For preparing polished blocks, bulk samples were crushed to a maximum particle size of 1 mm, mounted into epoxy resin, ground and polished. The petrographic composition was determined by maceral analysis. The petrographic composition of a polished block was determined by counting at least 300 points in normal reflected light for the determination of huminite and inertinite macerals. Then the counting was repeated by counting also 300 points in the fluorescent mode, which was used to determine liptinite macerals.

In addition to the petrographic analysis, each sample was also analyzed with standard procedures (DIN, ASTM, ISO norms) for its ash yield and moisture content, total sulphur and carbon contents, and for the gross calorific value at the dry ash free basis (as “Hobvp”). These analyses were performed in the chemical laboratory of the Šolski center Velenje (“School Centre Velenje”), where, at that time, a wealth of proximate and ultimate coal analyses were carried out for the Velenje Lignite Mine.

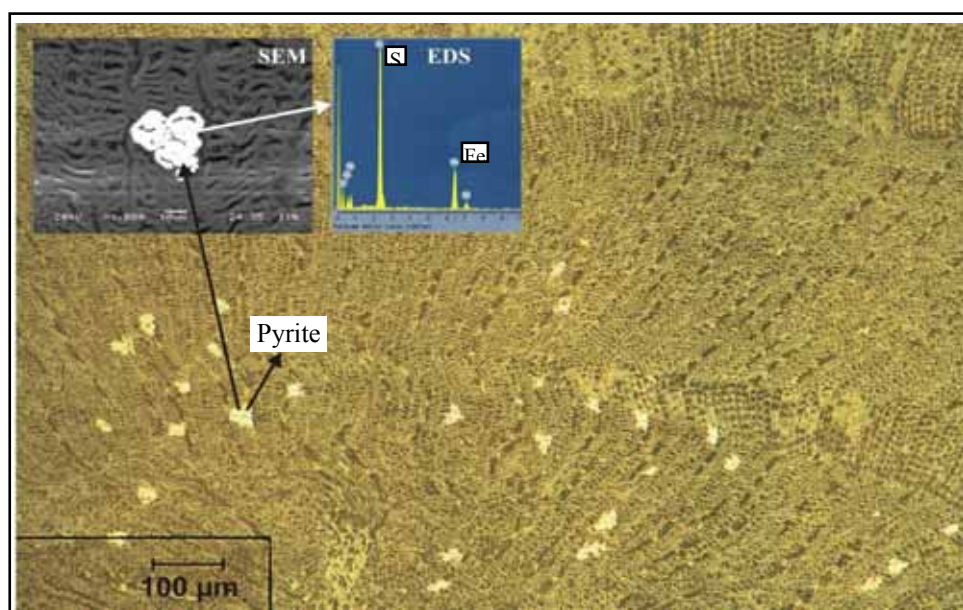
The maceral classification and nomenclature were strictly used after the ICCP classification from 1971 and 1975, respectively, as already presented from STACH et al. (1982) and BUSTIN et al. (1985) in **Tab. 6.3 (Chap. 6.2)**. Prior to the discussion of the results of the micro-petrographic analysis of the two boreholes, the presentation of macerals of the Velenje lignite will be given in the succeeding chapter.

#### **6.4.1.3. Microscopic appearance of macerals composing the Velenje lignite**

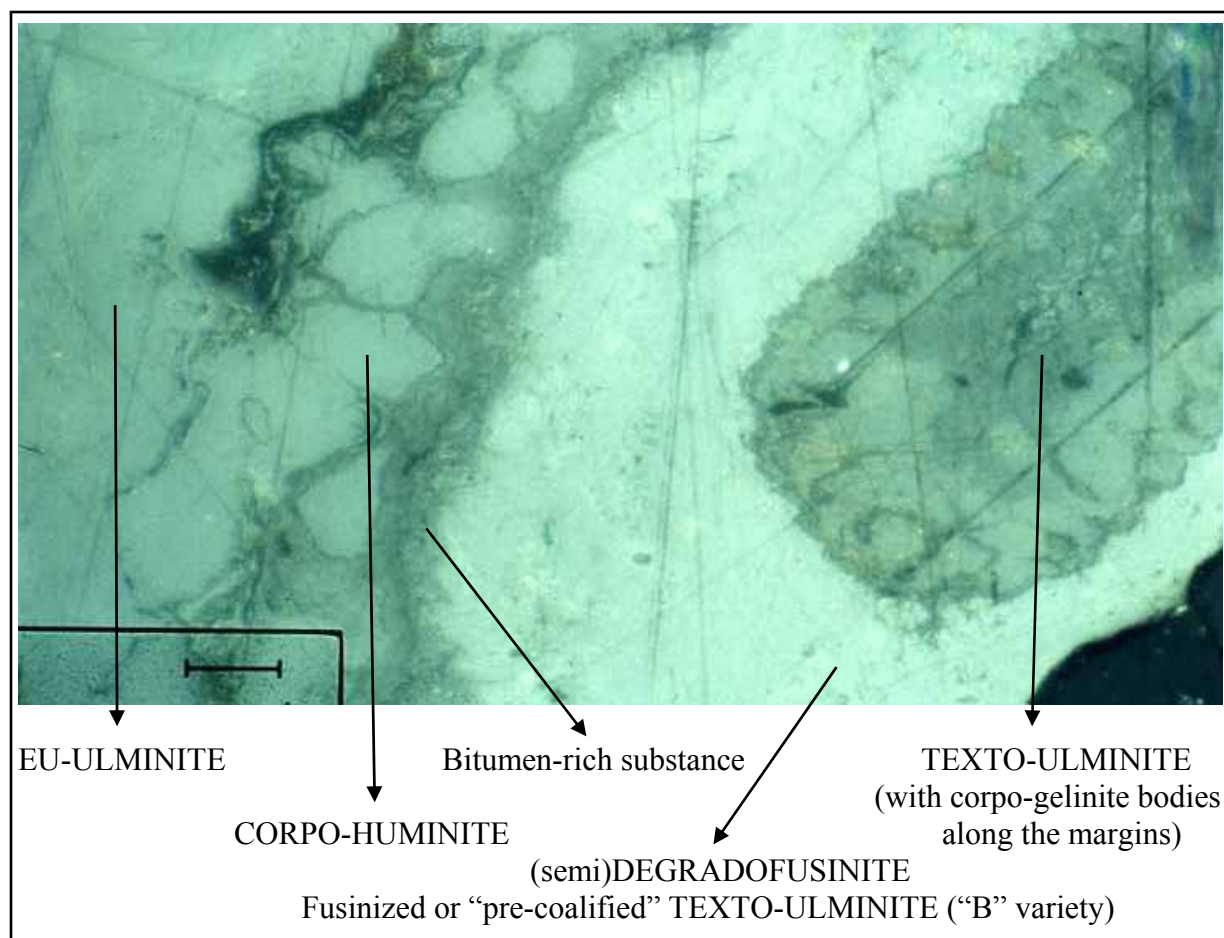
The micro-photos in this chapter present usual macerals that compose the Velenje lignite. Most images were taken in reflected white light (**Figs. 6.48 to 6.56**) or in fluorescent mode (**Figs. 6.57 to 6.59**). Scanning electron microscope images (SEM) (low vacuum) and spectra of chemical elements achieved by energy dispersive spectroscopy (EDS) are added in **Fig. 6.49**. Microscopy on the SEM was done at the National Building and Civil Engineering Institute in Ljubljana with generous help of Ana MLADENVIČ. Some more SEM images and elemental spectra are added in **Chap. 8.5.2** reporting on mineralogical investigations.



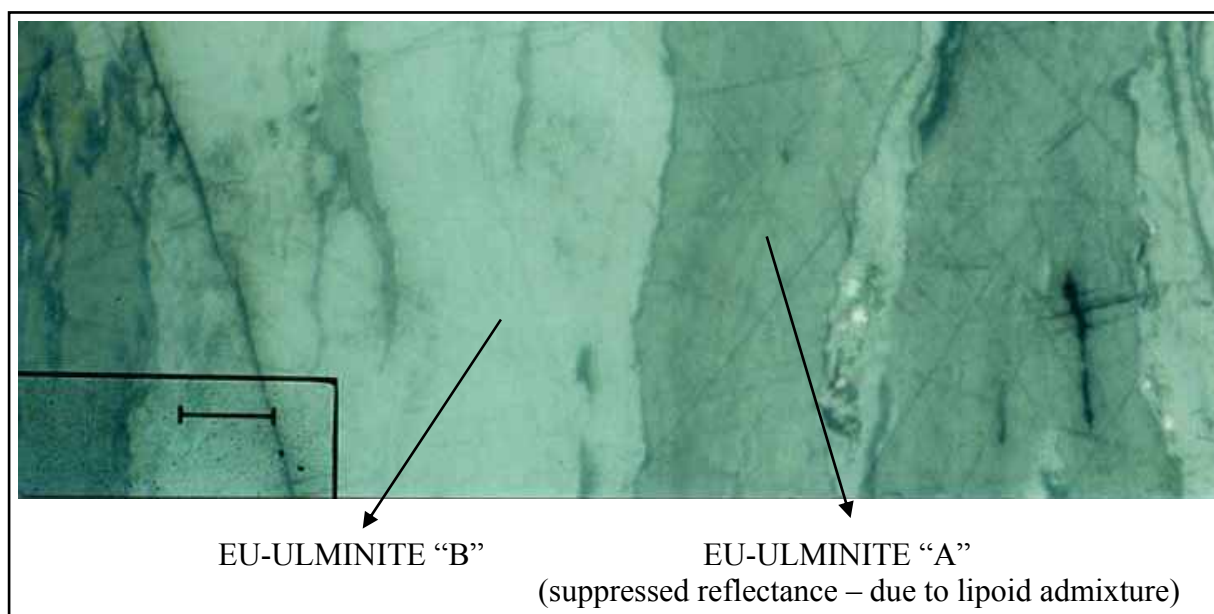
**Fig. 6.48:** Textinite (a) and textu-ulminite (b) with phlobaphinite (corpo-gelinite). a) Yellow internal reflections result from the still remaining considerable cellulose yield. Linear grinding scratches are visible due to bad polishing. The very bright substance is the not removed grinding/polishing material. The wood shows high resistance of lignin-rich cell walls typical of a coniferous wood, e.g. *Sequoia* (STACH et al., 1982, p.231, 232). (Reflected light – in oil immersion (a) and in air (b); scale bars are 50  $\mu\text{m}$ ).



**Fig. 6.49:** Textinite showing an excellently preserved cellular structure, which indicates annual rings. The latter confirm the presence of seasons during peat accumulation. Cells are partly replaced by pyrite/markasite. In the upper left corner, SEM image and elemental spectrum (EDS) are added, the latter clearly showing S and Fe contents which compose pyrite/markasite. (Reflected light – in air).

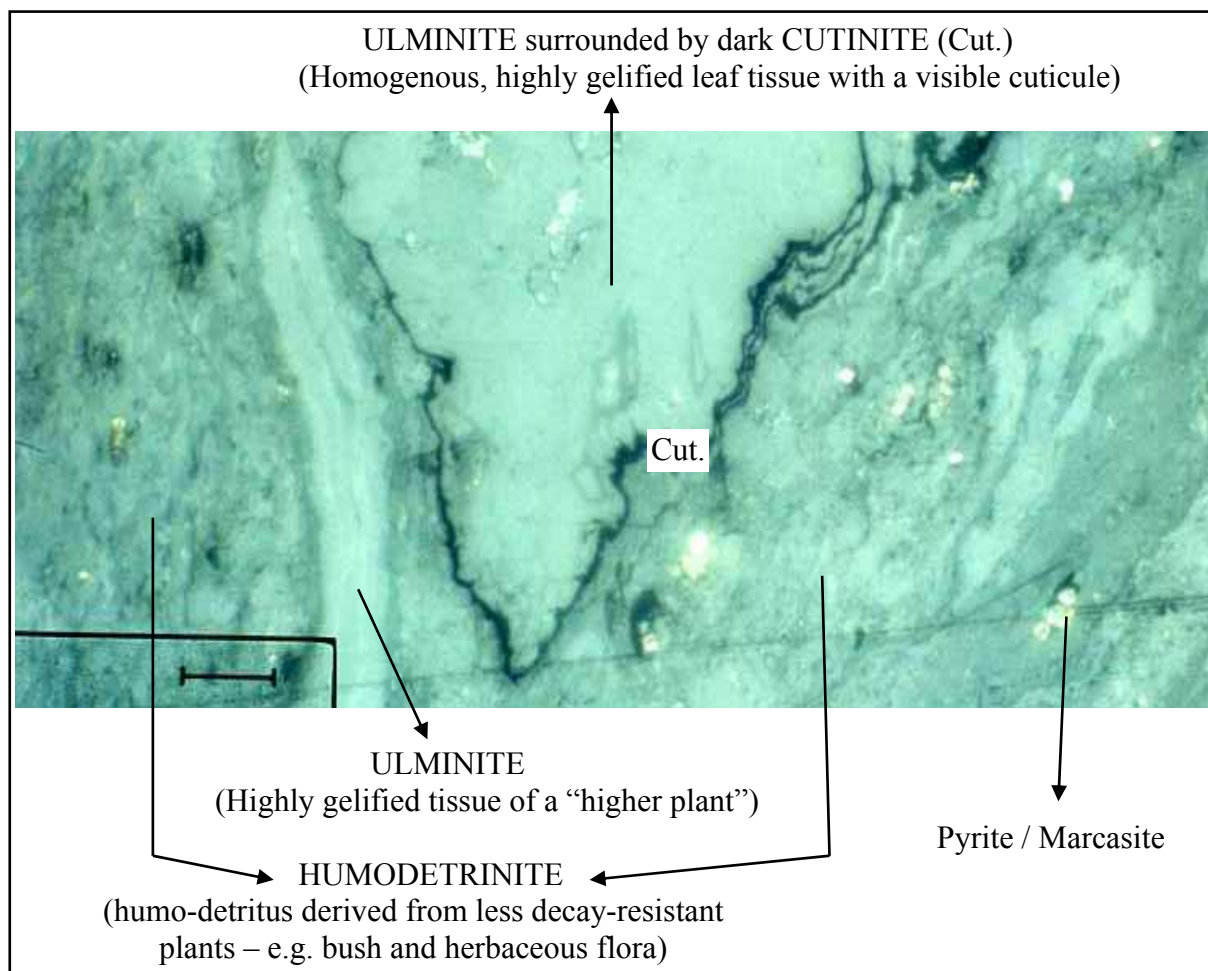


**Fig. 6.50:** Tissue macerals, differently affected by early coalification processes. (Reflected light – oil immersion; scale bar in the lower left corner is 50  $\mu$ m).

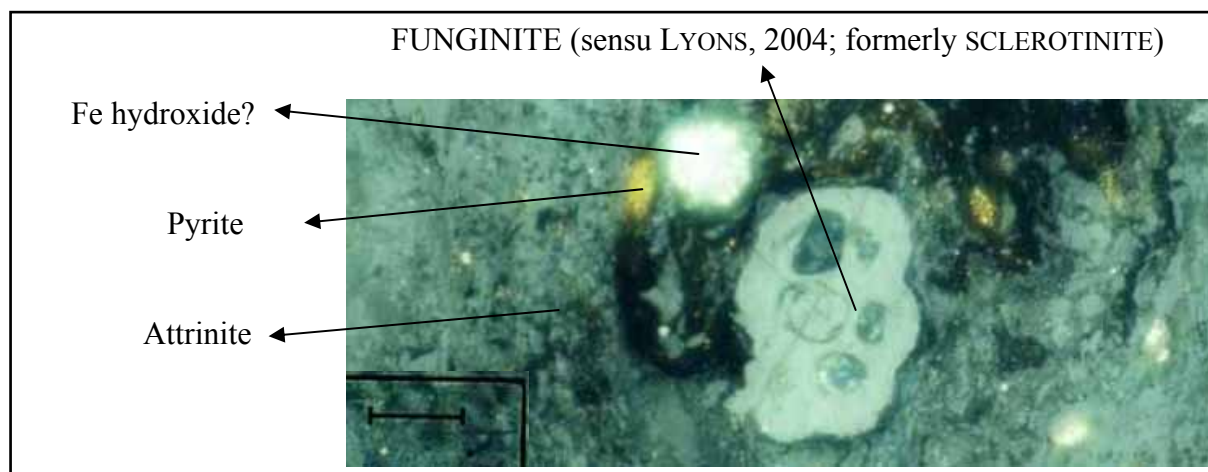


**Fig. 6.51:** “A” (dark) and “B” (bright) variants of ulminite. (Reflected light – oil immersion; scale bar in the lower left corner is 50  $\mu$ m).



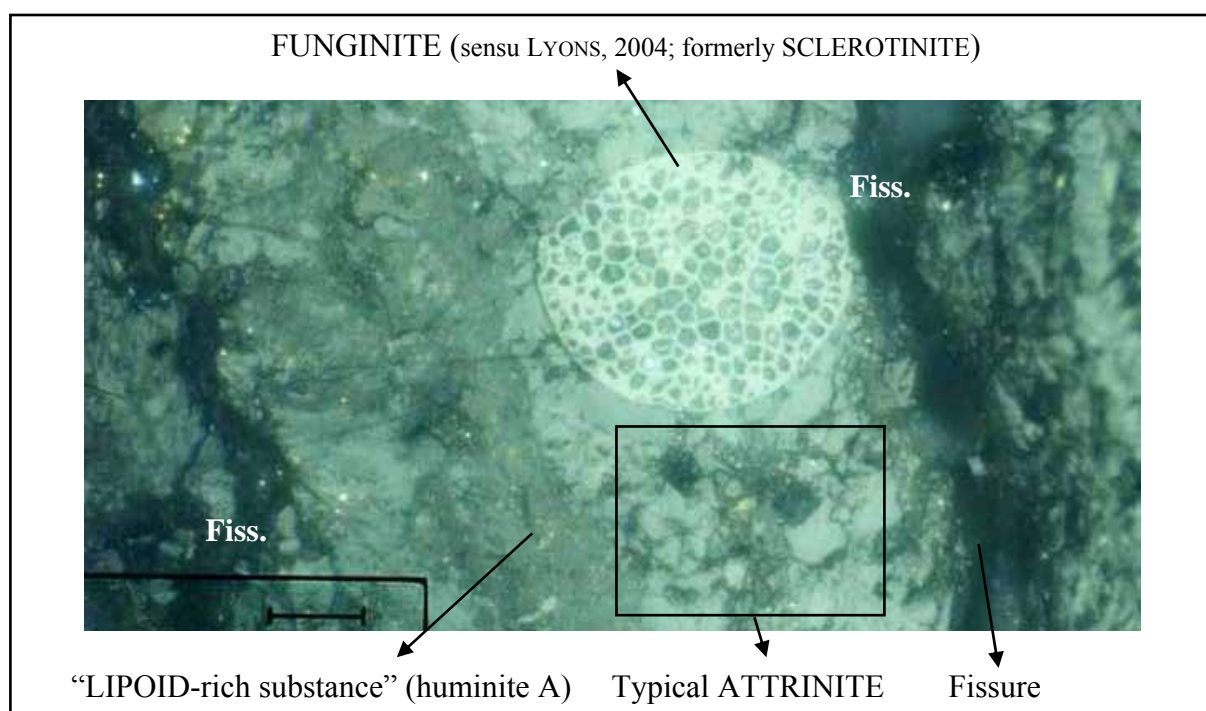


**Fig. 6.52:** Telinite (mesophyll huminite surrounded by cutinite) in detrital matrix. (Reflected light – oil immersion; scale bar is 50  $\mu\text{m}$ ).

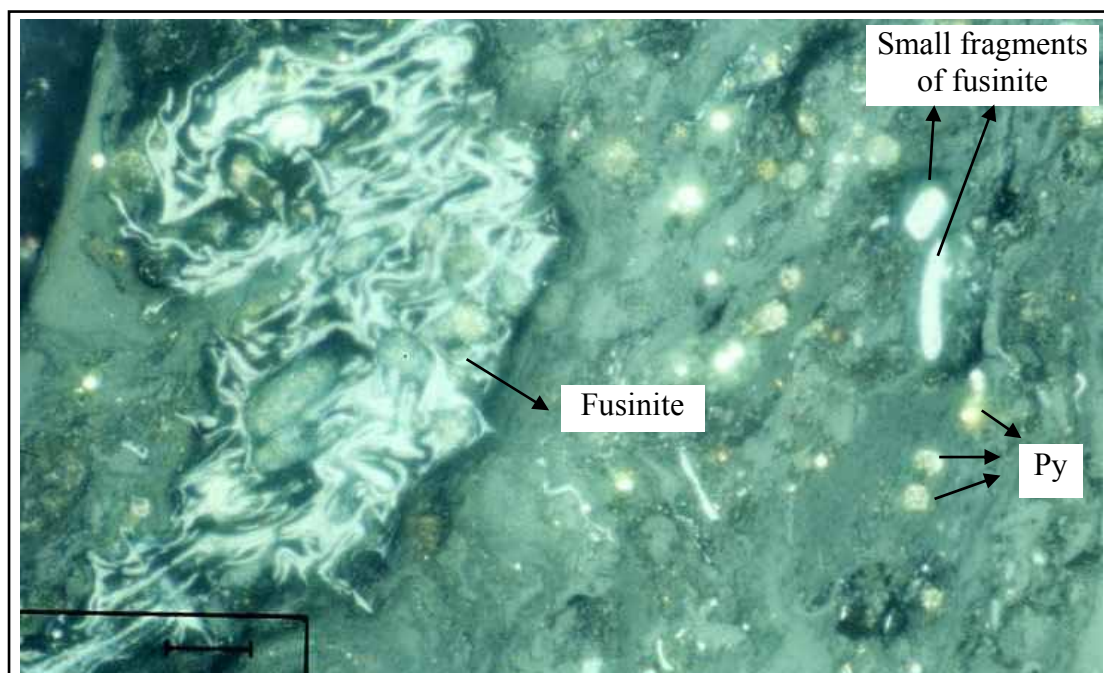


**Fig. 6.53:** Heterogeneous humodetrinite (detrinite to attrinite) rich in lipoid (dark grey) substances, and a thick-walled funginite in the middle of the photo. Funginite (LYONS, 2004) was formerly termed as sclerotinite (see also footnote at the end of Chap. 6.2), which included all strongly reflecting fungal remains such as hyphae, mycelia, plectenchime, spores and sclerotia (STACH et al., 1982, p.136). (Reflected light - oil immersion; scale bar is 50  $\mu\text{m}$ ).

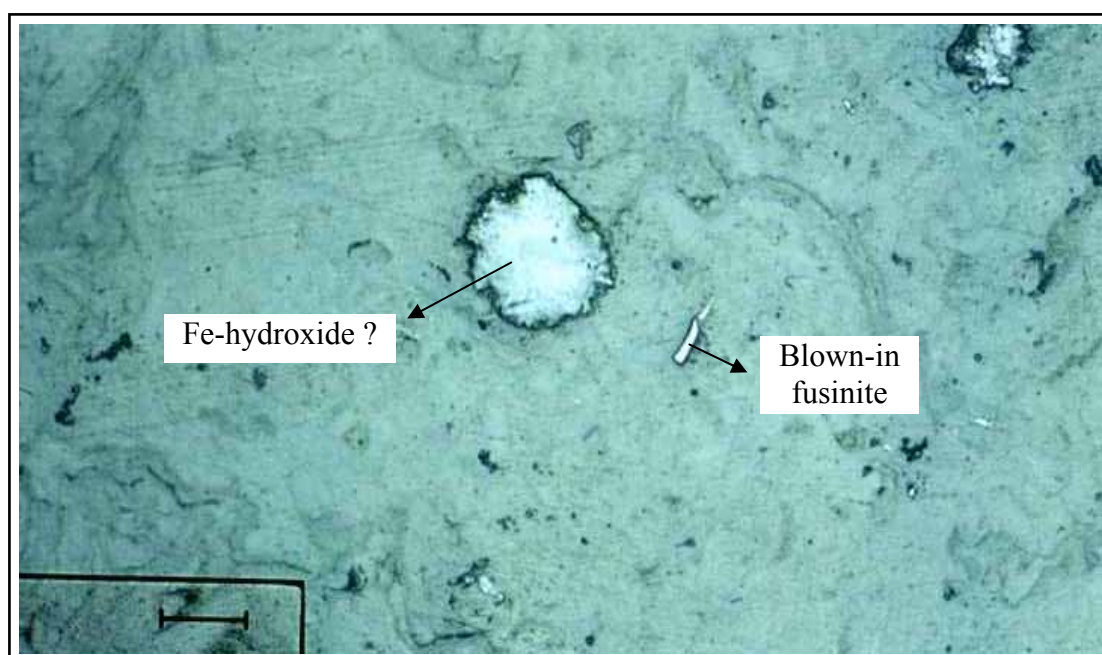




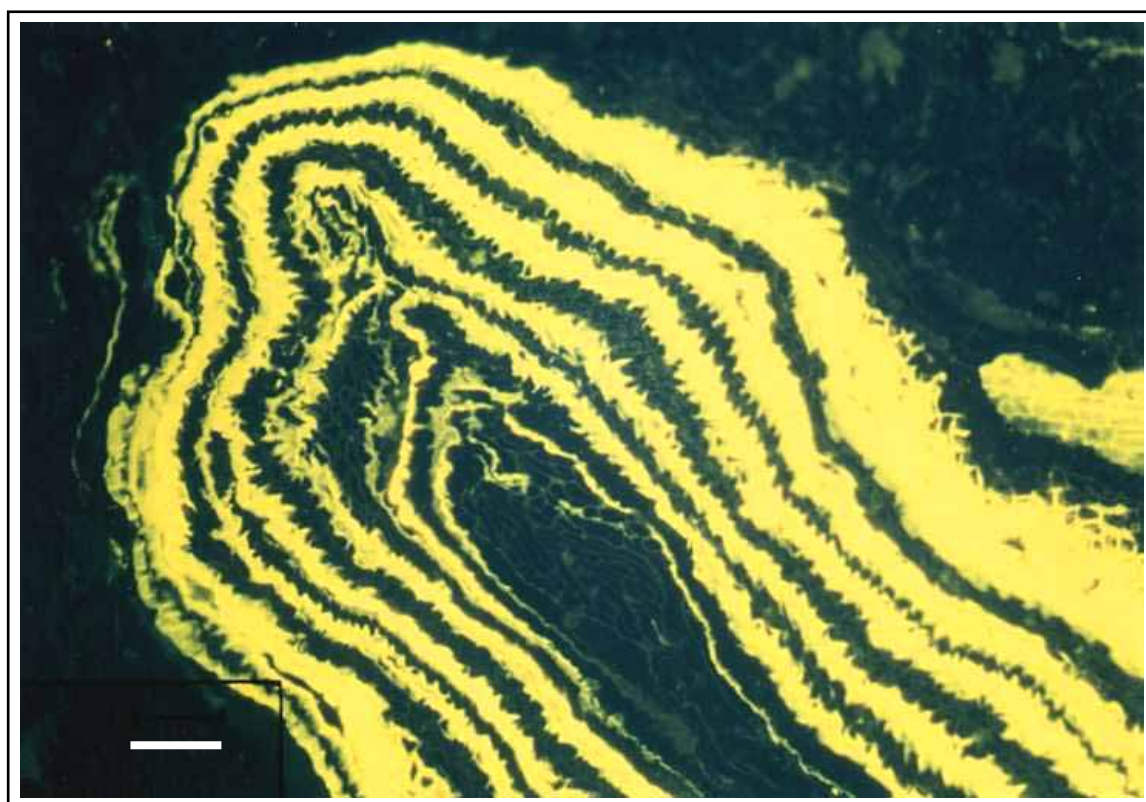
**Fig. 6.54:** Thin-walled multi-cellular funginite in a typical attrinite matrix composed of small, bright, well edged detrital particles and of darker lipoid (hydrogen enriched) substances. Typical funginite (formerly fungal sclerotinite) in this photo is well known in the literature as the *Sclerotites Brandonianus*. Fissures (black; Fiss.) are developed due to contrasted compositional and mechanical properties. (Reflected light – oil immersion; scale bar in the lower left corner is 50  $\mu\text{m}$ ).



**Fig. 6.55:** Typical large (pyro)fusinite in detrital groundmass with small scattered fragments of fusinite. Visible is also framboidal pyrite (Py). (Reflected light - oil immersion; scale bar is 50  $\mu\text{m}$ ).

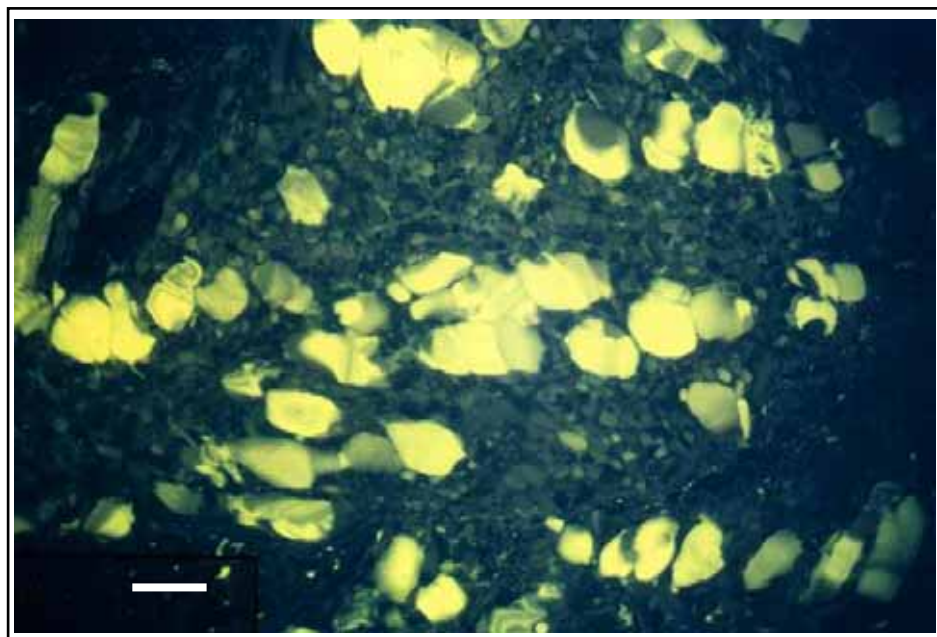


**Fig. 6.56:** Densinite groundmass. Some of very small rounded pores may result from fungal activity. Larger pores are inter-particle pores. Fe-hydroxide (relatively high reflection) was primarily most probably pyrite. (Reflected light – oil immersion; scale bar is 50  $\mu\text{m}$ ).

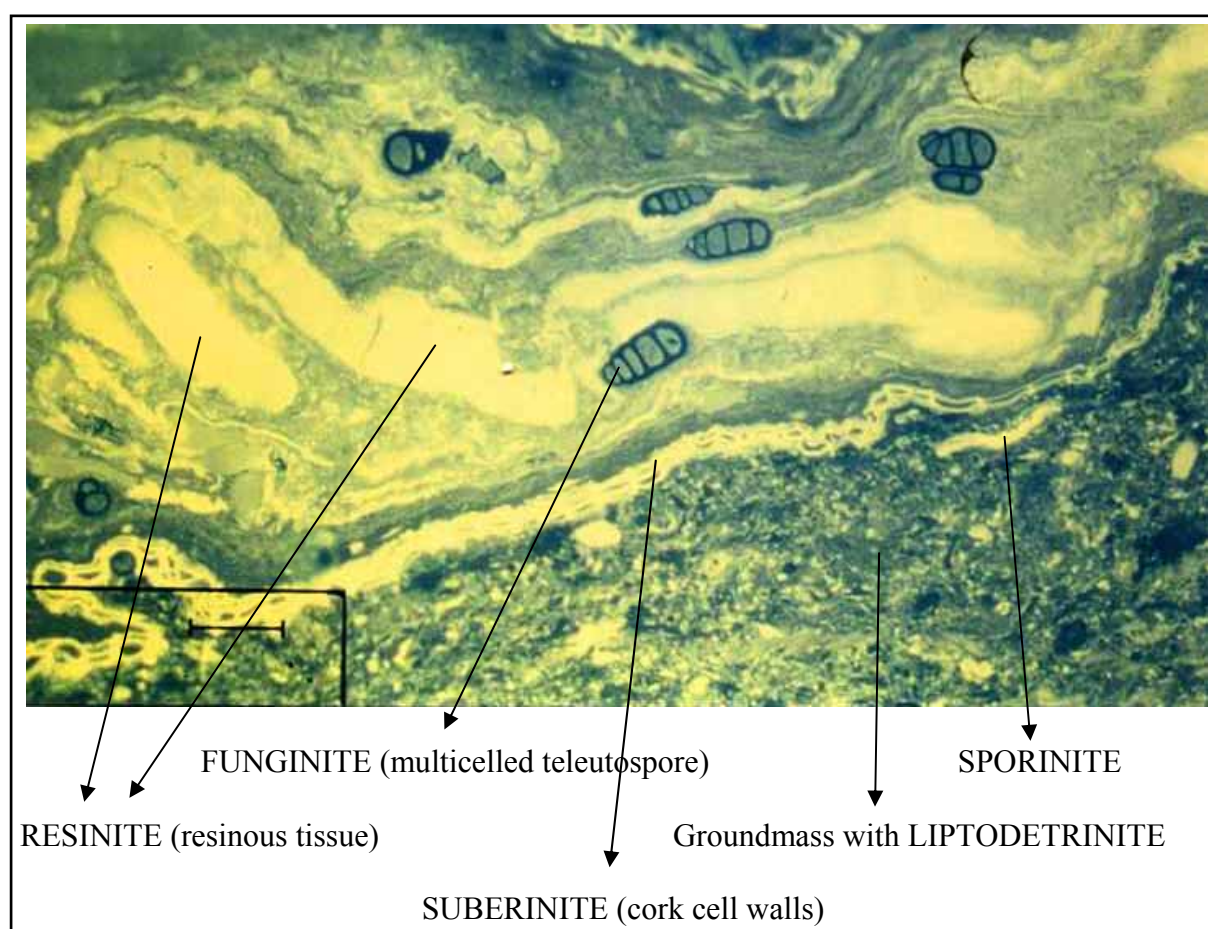


**Fig. 6.57:** Strongly yellow fluorescing liptinite macerals (cutinite). Intensity of fluorescence of low-rank coals is higher than of higher-rank coals. (Blue light irradiation - in air; scale in the lower left corner is 50  $\mu\text{m}$ ).





**Fig. 6.58:** Resinite. Large resinite bodies exhibit strong yellow fluorescence, whereas small resinite bodies are weakly fluorescing. Maybe root tissue. (Blue light irradiation – in air; scale bar is 50  $\mu\text{m}$ ).



**Fig. 6.59:** Liptinite-rich lignite. (Blue light irradiation - in air; scale bar is 50  $\mu\text{m}$ ).

#### 6.4.1.4. Results of micro-petrographic analysis in boreholes P-9k/92 and P-8z/92

Data basis of micro-petrographic analysis for both boreholes is presented in **Tabs. 6.14** and **6.15**. **Fig. 6.60** shows the vertical variation of the ash yields and of the sulphur contents, and also the average contents of the three basic maceral groups as well as average values of petrographic indices for the separated units and subunits. The ash yield was already discussed in the megascopic description of the core profiles in **Chap. 6.4.1.1** and will not be repeated here. From the petrographic domain of the seam analysis in borehole P-9k/92, the groundwater influence index (GWI; see more in the continuation of the text, and the equation for GWI) fits well to the ash yield, i.e., to the “exponential-like” decreasing values from the bottom towards the upper part of the lignite seam. The ash yield from proximate analysis and mineral matter content from microscopic analysis mostly refer to adventitious inorganic matter originating mainly from fluvial input. The latter was of relatively high energy and variable in spatial and temporal occurrence. More extreme fluvial input events might cause the formation of sediments with low and/or almost no organic matter content, the latter occurring as non-coaly clastic partings. For these reasons, ash yields and GWI values are not only relatively high but are also the most variable in the lowermost part of the seam.

##### 6.4.1.4.1. Maceral groups

The percentage of maceral groups (in vol. %) in both boreholes clearly show the predominance of the huminite macerals as typical for humic coals (**Fig. 6.60**). In borehole P-9k/92, in the lower three (sub)units I to II-b, the total huminite contents range from 81 to 94 % and on average below 90 %, respectively. In the upper three units, from II-b to III-b, the total huminite contents are even higher. There they vary from 90 to 97 % and average at about 92.5 %.

Liptinite and inertinite contents are highly subordinated to those of huminite (**Fig. 6.60**). Both groups are higher in the lower three units from I to II-b, and the liptinite macerals are somewhat more abundant than the inertinite ones. Liptinite contents in units I to II-b vary between 5 and 13 % (with the highest average of 10 % in subunit II-b). Inertinite macerals can in some samples reach an extreme content of 5 to 10 %, but their average is at less than 3 %. The highest inertinite values result from the content of degradofusinite. The content of inertinite macerals gradually decreases upward the seam profile.

The highest ash yield together with the highest GWI index (both mostly characterized by the fluvial mineral matter input), relatively the highest liptinite and the highest inertinite contents, which are in fact environmentally contrasted petrographic elements (the first being typically concentrated, at least partly, in more anaerobic and the second in more aerobic environments), and considerable predominance of xylite containing lithotypes (including a great share of resin-rich conifers) (**Fig. 6.46**) clearly show a relatively high and alternating energy environment in the time and space of formation of the bottom of the lignite seam (**Fig. 6.60**). By the maceral analysis in the continuation it will be confirmed that the bottom of the seam was developed from the alternating wet to dry forest swamp.

**Table 6.14:** Maceral composition, mineral matter content (in vol. %), ash yield and total sulphur content (in wt. %), and calculated petrographic facies indices of samples from borehole P-9k/92. Note that only percentages of the maceral groups ( $\Sigma$ Hum,  $\Sigma$ Lipt,  $\Sigma$ Inert) are calculated on the mineral matter free (mmf) basis. Ash yield and total sulphur contents are cited on the dry basis (db). Abbreviations are given at the end of the table. Equations for GWI, GI and TPI are given at the bottom of Tab. 6.15. (From MARKIČ & SACHSENHOFER, 1997).

Sample N°	Depth m	HUMINITE						LIPNITE		INERTINITE				MIN.MATTER		FACIES INDICES											
		Tx-A	Tx-B	Tx-C	Ulm-A	Ulm-B	Corph	Atrm	Dens	$\Sigma$ Hum	Su-Re	SCRFL	$\Sigma$ Lipt	Fus	Degfus	Maer	Scler	Inder	$\Sigma$ Inert	Pyr	M.M.	Ash	S <sub>tot</sub>	GWI	GI	TPI	
UNIT IIb																											
96	456.9	32	1	10	11	3	5	1	7	24	95	1	3	4	0	0	1	0	0	1	1	1	12	2.75	0.02	1.38	1.97
95	458.0	34	1	14	7	1	5	2	27	2	97	1	2	3	0	0	0	0	0	0	1	4	17	2.76	0.07	0.50	2.21
94	459.0																					11	3.09				
93	460.1	12	4	10	13	1	6	3	12	31	92	1	4	5	0	1	1	1	0	3	0	0	10	2.28	0.03	2.32	1.11
92	461.4	15	1	11	13	1	6	3	4	36	90	2	4	6	0	1	2	0	1	4	0	0	8	1.88	0.03	3.43	1.19
91	463.3	6	1	11	13	1	6	3	16	33	92	1	5	6	0	1	0	0	1	2	1	2	13	2.31	0.06	2.79	0.84
90	465.2	6	0	22	17	1	5	1	5	35	94	1	5	6	0	0	0	0	0	0	1	2	7	1.82	0.03	7.36	1.30
89	466.5	4	3	11	14	1	10	2	20	22	90	1	6	7	1	0	1	0	1	3	2	3	12	2.52	0.06	2.10	1.07
88	468.0	10	1	10	13	2	9	2	19	29	95	0	2	2	0	1	1	1	0	3	0	0	13	2.38	0.02	2.20	0.96
87	470.3	21	1	12	14	2	4	3	12	22	92	3	4	7	0	1	0	0	0	1	0	1	14	2.25	0.05	1.68	1.68
86	471.7	4	2	15	15	1	8	2	30	13	94	1	5	5	0	0	1	0	0	1	2	3	18	3.00	0.06	1.53	1.07
	473.1																										
85	473.4	7	2	9	15	1	8	1	15	24	90	0	6	7	0	1	2	0	0	3	1	9	16	2.32	0.12	2.50	1.05
84	474.4																										
83	474.9	7	5	11	15	1	9	1	22	19	94	0	6	6	0	0	0	0	0	0	1	4	18	2.87	0.06	1.65	1.20
82	477.0	13	2	11	9	1	11	3	17	24	95	1	4	5	0	0	0	0	0	0	3	4	13	2.73	0.08	1.84	1.22
81	478.1	12	3	6	15	2	5	1	22	21	92	0	7	7	0	0	1	0	0	1	4	5	14	2.96	0.07	1.38	1.00
80	480.0	12	4	10	13	2	10	0	17	20	90	1	5	6	0	3	0	0	1	4	2	2	12	3.08	0.02	1.62	1.38
79	481.6	12	7	10	12	1	5	2	32	7	95	2	3	5	0	0	0	0	0	0	2	7	23	3.05	0.10	0.73	1.26
78	483.2	20	3	10	10	3	5	3	20	14	91	2	5	7	0	1	1	0	0	2	2	3	15	2.60	0.07	1.07	1.54
	484.9																										
UNIT IIIa																											
77	485.3	26	2	11	9	1	6	2	7	28	95	0	3	3	0	0	2	0	0	2	1	3	10	2.40	0.06	1.69	1.54
76	486.7	18	5	8	16	1	4	1	17	22	95	0	4	4	0	0	1	0	0	1	2	3	13	2.59	0.04	1.33	1.33
75	488.8	19	4	10	15	2	8	0	11	19	92	1	6	7	0	0	1	0	0	3	4	3	13	3.47	0.05	1.59	1.93
74	490.2	7	7	7	13	2	8	1	36	5	94	1	3	4	0	1	0	1	0	2	2	8	23	3.32	0.11	0.72	1.10
73	491.6	27	2	19	12	4	5	3	4	21	97	2	1	3	0	0	0	0	0	0	0	0	8	2.31	0.03	1.94	2.88
72	492.9	4	4	8	15	2	8	4	11	33	90	1	8	9	0	0	0	0	1	1	1	9	9	2.35	0.06	3.50	1.02
71	494.4	8	2	8	15	2	10	2	14	28	92	0	5	5	2	1	0	0	0	3	2	3	11	2.45	0.06	2.50	1.17
70	495.2	28	2	7	4	12	12	0	17	11	95	1	4	5	0	0	0	0	0	0	2	2	16	2.42	0.02	0.98	2.32
69	496.1	13	3	3	15	1	12	1	14	28	90	1	2	3	0	1	4	1	1	7	0	0	12	2.22	0.01	2.06	1.04
68	497.8	16	1	5	9	5	13	1	11	28	90	2	4	6	0	0	3	0	1	4	1	1	9	1.75	0.02	2.21	1.19
	499.0																										



Table 6.14 – continuation

Sample N°	Depth m	HUMINITES										LIPINITES		INERTINITE				MIN. MATTER		FACIES INDICES							
		Tx-A	Tx-B	TxU-A	TxU-B	Ulm-A	Ulm-B	Corpoh	Attrin	Dens	ΣHum %mmf	Su-Re	SCREL	ΣLat %mmf	Fus	Degfus	Maer	Scler	Indetr	ΣInert %mmf	Pyrit	M.M. vol %	Ash weight % (db)	GWI	GI	TPI	
UNIT IIC																											
67	499.3	6	1	14	6	2	6	1	37	12	90	1	4	5	1	1	1	0	1	5	5	6	16	3.65	0.08	0.91	0.74
66	501.0	5	2	9	12	1	4	2	35	9	84	2	5	8	0	7	0	0	1	8	3	6	12	2.67	0.10	0.86	0.80
65	502.6	11	5	10	14	1	10	0	22	19	93	1	3	4	0	2	1	0	0	3	1	1	12	2.21	0.01	1.45	1.21
64	504.1	5	0	7	17	1	6	0	47	7	97	0	3	3	0	0	0	0	0	0	2	7	21	2.59	0.08	0.73	0.67
63	505.9	9	2	9	12	3	8	0	42	2	92	1	5	6	0	0	1	0	0	1	2	6	23	2.34	0.07	0.66	0.96
62	507.5	22	0	12	9	4	4	1	33	5	94	1	4	5	0	0	1	0	0	1	2	4	16	1.93	0.06	0.65	1.33
	508.8																										
61	509.2	3	1	13	13	3	6	0	43	8	93	0	5	5	0	1	1	0	0	2	1	3	15	2.09	0.03	0.94	0.75
60	510.8	10	3	4	16	2	15	0	18	22	94	1	4	5	0	0	1	0	0	1	2	4	19	1.74	0.04	1.94	1.22
59	512.7	2	6	7	10	2	12	1	38	7	92	1	7	8	0	0	0	0	0	0	2	7	19	1.41	0.10	0.85	0.89
UNIT IIB																											
514.2																											
58	514.6	7	4	9	7	3	6	2	27	13	86	2	10	13	0	1	0	0	0	1	2	9	21	2.27	0.14	1.05	0.95
57	516.2	16	5	16	4	5	6	2	26	2	90	2	5	7	0	2	0	0	0	3	3	9	22	3.04	0.14	0.74	1.93
56	517.3	7	6	9	6	4	3	1	30	11	84	2	9	12	0	2	1	0	0	4	1	9	16	1.84	0.13	0.81	0.86
55	518.6	5	8	5	8	2	5	1	33	6	85	1	10	13	0	1	1	0	0	2	4	14	25	2.72	0.21	0.61	0.85
54	519.8	3	5	10	8	5	5	1	36	3	87	4	5	10	0	2	0	0	1	3	2	12	19	2.24	0.17	0.71	0.95
53	522.0	11	4	13	6	1	3	2	31	5	86	2	7	10	0	3	0	0	0	4	1	12	18	2.13	0.19	0.65	1.11
52	523.5	17	3	19	6	1	4	3	27	0	91	2	5	8	0	0	0	0	1	1	3	12	21	2.49	0.19	0.69	1.96
51	525.4	26	5	18	9	3	2	2	12	2	90	1	6	8	0	0	1	0	1	2	1	12	20	2.73	0.18	0.84	4.33
UNIT IIA																											
50	527.0	9	7	16	17	1	5	3	22	8	93	1	5	6	0	0	0	0	1	1	2	5	17	3.15	0.09	1.28	1.93
49	528.7	5	7	8	7	0	2	1	26	0	88	1	4	7	0	1	1	0	1	5	3	36	35	3.03	0.67	0.49	1.11
48	530.4	6	6	8	7	1	5	0	42	3	89	1	6	8	0	1	0	0	2	3	3	12	17	2.95	0.15	0.43	0.73
47	532.0	6	6	6	13	4	7	0	26	1	88	1	5	8	1	1	0	0	1	4	2	22	24	2.18	0.32	0.78	1.59
46	533.6	11	9	9	11	0	6	1	22	1	85	1	3	5	0	4	1	0	3	10	3	18	21	2.72	0.28	0.64	1.96
45	535.4	5	7	14	22	3	3	1	25	7	94	1	3	4	0	1	0	0	1	2	2	7	14	1.82	0.09	1.32	1.72
44	536.5	3	3	4	19	0	5	0	45	7	91	1	7	8	0	0	0	0	1	1	2	5	20	2.20	0.06	0.67	0.65
43	537.8	8	4	9	23	0	3	1	28	2	91	1	4	6	0	1	1	0	1	3	1	14	25	1.87	0.19	0.95	1.55
42	539.0	4	6	6	15	0	2	1	43	1	90	0	6	7	0	0	1	1	1	3	2	13	26	2.01	0.18	0.48	0.76
41	540.5	17	4	5	7	0	5	0	19	0	93	0	2	4	0	2	0	0	0	3	1	39	37	1.48	0.68	0.43	2.00
40	541.5	8	0	10	3	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	79	58	0.05	3.76	1.63	96

Table 6.14 – continuation

Sample	Depth m	HUMINITE										LIPTINITE		INERTINITE				MIN. MATTER		FACIES INDICES							
		Tx-A	Tx-B	TxU-A	TxU-B	Ulm-A	Ulm-B	Corpoh	Attrin	Dens	ΣHum %smmf	Su+Re	SCRF	ΣLipt %smmf	Fus	Degfus	Maer	Scler	Indstr	ΣInert %smmf	Pyrit	M.M. vol %	Ash weight % (db)	S <sub>oc</sub>	GWI	GI	TPI
UNIT I																											
39	542.1	15	4	18	10	0	3	3	30	1	94	0	3	3	0	1	1	0	0	3	2	11	19	2.46	0.17	0.73	1.66
38	543.0	8	1	9	15	0	10	0	15	19	90	1	6	8	1	0	0	1	0	2	1	14	32	2.84	0.18	2.12	1.29
37	543.9																						65	0.03			
36	544.5	3	1	6	32	0	8	2	23	3	92	0	7	8	0	0	0	0	0	0	3	15	27	2.10	0.22	1.89	2.00
35	545.5	4	1	8	13	1	8	1	18	3	85	0	5	8	1	2	2	0	0	7	3	33	30	1.72	0.61	1.50	1.61
34	547.5																						62	0.02			
33	547.7	1	0	2	12	0	8	2	31	2	89	1	6	11	0	0	0	0	0	0	2	35	44	2.08	0.66	0.81	0.76
32	549.2	5	1	5	16	0	7	0	23	7	94	0	4	6	0	0	0	0	0	0	3	32	43	2.55	0.50	1.21	1.13
31	550.7	4	0	6	11	0	8	1	18	12	91	0	6	9	0	0	0	0	0	0	3	34	46	1.86	0.59	1.73	1.00
30	552.0	13	1	21	15	0	8	2	13	6	91	0	3	3	1	2	1	0	1	6	2	13	25	2.20	0.19	1.83	3.05
29	553.2	0	2	0	10	0	4	1	24	11	81	0	6	10	0	2	2	1	1	9	5	36	39	4.17	0.73	1.04	0.46
28	554.5	4	3	7	14	0	9	1	24	6	82	1	9	12	0	2	2	1	0	6	2	17	34	3.83	0.27	1.26	1.19
27	555.8	2	3	2	10	1	9	0	20	10	90	0	3	5	0	2	1	0	0	5	3	37	45	3.21	0.65	1.32	0.87
26	557.0	0	0	1	14	1	8	0	25	2	94	1	2	6	0	0	0	0	0	0	2	46	40	3.92	0.90	1.04	0.89
	557.8																										

Maceral abbreviations as used in Tabs. 6.14 and 6.15:

Tx: textinite; TxU: texto-ulminite; Ulm: ulminite; A – “dark” variety, B – “bright” variety

Corpoh: corpo-huminite; Attrin: attrinite; Dens: densinite

Σ Hum: total huminite

Su + Re: suberinite + resinite(in situ); SCFRL: sporinite + cutinite + fluorinate + resinite (detrital) + liptodetrinite;

Σ Lipt: total liptinite

Fus: fusinite; Degfus: degradofusinite; Maer: macrinite; Scler: funginite (formerly sclerotinite); Indetr: inertodetrinite;

Σ Inert: total inertinite.

 M.M.: mineral matter; S<sub>wt</sub>(db): total sulphur (dry basis)

GWI: groundwater influence index; GI: gelification index; TPI: tissue preservation index

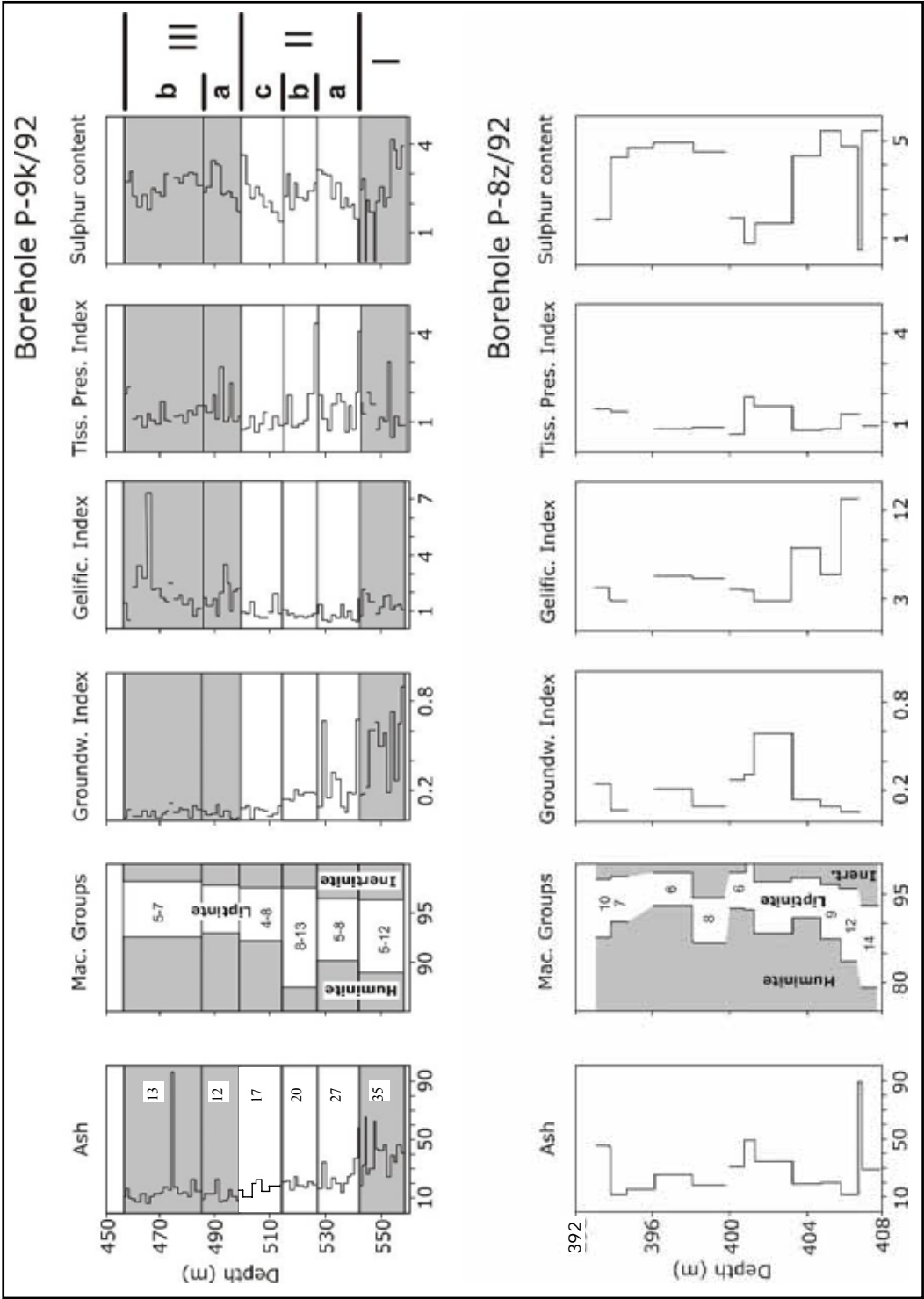
**Petrographic indices as cited in Tabs. 6.14 and 6.15**

$$GI = \frac{\text{texto-ulminite} + \text{eu-ulminite} + \text{corpohuminite} + \text{densinite} + \text{macrinite}}{\text{textinite} + \text{attrinite} + \text{fusinite} + \text{inertodetrinite}}$$

$$TPI = \frac{\text{textinite} + \text{texto-ulminite} + \text{eu-ulminite} + \text{corpohuminite} + \text{fusinite}}{\text{attrinite} + \text{densinite} + \text{macrinite}}$$

$$GWI = \frac{\text{corphuminite} + \text{mineral matter}}{\text{textinite} + \text{texto} - \text{uminite} + \text{eu} - \text{ulminite} + \text{atrinite} + \text{densinite}}$$

**Fig. 6.60:** Variation of ash yield (wt. %; db), maceral groups (vol. % mmf), groundwater index (GWI), gelification index (GI), tissue preservation index (TPI), total sulphur content (wt. %; db), and gross calorific value (GCV in MJ/kg; db) in boreholes P-9k/92 and P-8z/92. (From MARKIĆ & SACHSENHOFER, 1997). Note the great difference in the depth scale between the two boreholes. In the ash log and for liptinite group, average contents for the units are cited.



Upwards the seam profile (**Fig. 6.60**), general environmental conditions uniformed and stabilised. This is reflected again in the indicators as the lowering of the ash yield and its constancy, the ground water influence decrease and its constancy, as well as in the decrease and constancy of liptinite and inertinite maceral contents. Also in the thickest lignite split in borehole P-8z/92 (**Fig. 6.60**), the total liptinite content decreases upwards. A similar situation, with an exception in the middle of the split, is true for the inertinite maceral group as well. Therefore, an environmental explanation can be somewhat similar as for the bottom part of the lignite seam in borehole P-9k/92. However, in borehole P-8z/92, situated on the northern margin of the peat basin, which was influenced by alluvial fan progradation, more pronounced petrological variability of the lignite resists throughout the whole lignite profile.

#### 6.4.1.4.2. Application of the petrographic facies indices

Quantitative micro-petrographic data-sets, comprising an extensive number of individual maceral contents (e.g. ranges of huminite, liptinite and inertinite macerals in **Tabs. 6.14** and **6.15**) can be reduced to a smaller number of petrographic indices. These are expressed in the forms which hold information about the most important and basic features of the peat-forming environments. The development of facies indices by different authors is reviewed e.g. in DIESSEL (1992), and the mentioned author developed his own petrographic indices as well. These are the well known gelification index (GI), which contrasts gelified with non-gelified macerals, and the tissue preservation index (TPI), expressing the relationship between well preserved tissues versus highly degraded components (DIESSEL, 1986). For soft brown coals, "DIESSEL's" (1986) GI and TPI were later slightly modified by KALKREUTH et al. (1991) and have also been used for the Velenje lignite by MARKIČ & SACHSENHOFER (1997) (**Tabs. 6.14** and **6.15**). Equations for GI and TPI are given below **Tab. 6.15**. Two additional petrographic indices were introduced by CALDER et al. (1991), termed as the vegetation index (VI) and the groundwater index (GWI). In the case of Velenje, the VI closely corresponds to the TPI, and will thus be omitted in the continuation. GWI (see equation under **Tab. 6.15**) contrasts mineral matter content (and corpohuminite, which is a rare component) to huminite macerals. Vertical variations of the three petrographic indices are shown in **Fig. 6.60**. DIESSEL (1986) proposed coal facies diagrams, which are cross-plots between GI and TPI. In the cross-plots, he distinguished among the following peat-forming environments: marsh and fen, characterized by high GI values (above 10) of resulting maceral composition, relatively wet forest swamp with GI values mostly between 1 and 5, and relatively dry forest swamp with GI values below 1. Lignites from paleo-forest swamps are characterized by TPI values between 1 and 3, whereas lignites originating from fen and marsh environments by TPI values around 1 and below. GI versus TPI values for separate units in boreholes P-9k/92 and P-8z/92 are presented in **Fig. 6.61**.

In the P-9k/92 lignite profile, GWI significantly decreases upwards, whereas GI increases (**Fig. 6.60**) in the same direction. The decrease in GWI is the most pronounced at the lower-most part of the seam, whereas GI increase is most clearly pronounced in the upper-most part of the seam profile. TPI does not express so significant trends as the previously mentioned indicators. In unit I, TPI correlates negatively with ash yield ( $r = -0.74$ ). More significant than absolute values of TPI is the variability of this index, which is high to moderate in units I to II-b, and in unit III-a. In units II-c and III-a, the TPI is uniform, showing stable environmental and floristic conditions. However, in unit III, a slight decrease in TPI can be observed in the upward direction, which can be correlated with increasing GI in the same direction. This fact can be explained by a gradual establishment of more fen-like environments with dwarf plants,



which gave a greater share of fine-detrital peat-forming biomass that was easily gelified in a near-neutral to slightly alkaline environment.

In the P-8z/92 lignite profile, the most “regular” is the upward decrease of GI. This is just the opposite trend than in the case of the P-9k/92 profile. Regarding greatly different environmental conditions, this is not very surprising. An extreme value of GWI at the depth around 402 m and a low GI value indicate that gelification processes require a calm environment. The same can be concluded from a negative correlation between GI and GWI as evident in the P-9k/92 lignite profile.

The question why TPI is not a more discriminating tool in facies interpretation is somehow surprising. Namely, it would be expected that the xylite-rich lignite (e.g. units I and II-a in P-9k/92 – see also **Chap. 6.4.1.1**) which is supposed to originate from forest swamps would reflect high TPI (especially if coniferous), and that fine-detrital lignite originating from more dwarf plant progenitors from the upper part of the seam would reflect lower TPI. However, in microscopic maceral analysis, this distinction may be obscured due to dimensional limitations, both of the microscopic objective field and especially of the  $50 \times 50 \mu\text{m}$  square micro-areas as applied when performing a strictly quantitative maceral analysis by point counting. The xylite-rich facies and low degree of gelification in the lower part of the seam can be explained by a relative predominance of the coniferous *Taxodium* flora over the fern *Osmunda* flora as revealed by pollen analysis in borehole P-11r/98 (BRUCH, 2000; and her personal information). Pollen grains of *Taxodiaceae* and of *Osmunda* highly prevail against pollen assemblages of *Tsuga* (hemlock-spruce), *Fagus* (beech), *Alnus* (alder) and *Carya* (hickory-nut).

#### 6.4.1.4.3. Sulphur content

Variation of the total sulphur content is presented in the right-most columns in **Fig. 6.60**. Total sulphur contents (in wt. % at the dry basis) in lignite samples with less than 50 % ash vary from 1.0 to 5.5 %. Non-coaly partings contain less than 0.05 % sulphur. Sulphur content is relatively higher and more variable in P-8z/92 (on average  $3.64 \pm 1.72 \%$ ) than in the P-9k/92 lignite profile (on average  $2.47 \pm 0.65 \%$ ). It is high regarding the lacustrine origin of coal. Such sulphur values are characteristic of coals influenced by marine waters.

In the P-9k/92 lignite profile, sulphur contents are the highest and most variable at the bottom of unit I, where they reach a maximum of 4.17 %, but fall rapidly upwards to values around 2 %. Sulphur contents correlate well with ash yields and with GWI, which both decrease in the same direction.

In subunits II-a, II-b and II-c, the sulphur contents clearly exhibit either generally increasing (II-a and II-c) or decreasing (II-b) trends. Changes in these trends excellently coincide with the boundaries between the units and subunits. This coinciding is considerably clearer than in the case of other indicators in **Fig. 6.60**, and can be regarded as a good proof that the units and subunits had been well ascertained already prior the detailed maceral and proximate analysis. The lowest sulphur contents in unit II are around 1.45 % and the highest are around 3.10 %, with a maximum of 3.65 % at the II-c/III-a boundary just below a stump (horizon).

In unit III, above the just mentioned stump, sulphur content reaches only 1.75 %, but increases then again to almost 3.50 % at the top of subunit III-a. In subunit III-b it ranges

from about 3.0 % at the bottom to around 2.0 % at the top. Interestingly, just below the lignite overlying marl the total sulphur content in lignite increases again rapidly to values between 2.75 and 3.10 %. This effect is somewhat similar to that of sulphur increase at the top of coal seams with marine roofs.

The correlation analysis between sulphur contents and ash yields shows either positive correlation in the case of samples in subunit II-b and in unit III, or it does not show any correlation. Another positive correlation would be expected between sulphur content and gelification, because both sulphate-reduction and the incorporation of the reduced sulphur into sulphur-bearing minerals (and/or sulphur bonding to organic molecules) and the gelification of organic matter are well known to be enhanced by bacterial activity in a prevailing (neutral to slightly) alkaline environment. However, this correlation is far from clear in the case of the Velenje lignite. The sulphur contents do not correlate in general with any of the other facies indicators. A general conclusion can only be made concerning the comparison between boreholes P-9k/92 and P-8z/92. In the first lignite profile, both gelification and sulphur contents are lower than in the second profile. A much closer vicinity of the carbonate bedrock and hence a more alkaline geochemistry in the case of the northern marginal P-8z/92 lignite profile can be a reasonable explanation for this fact. Non-regularity in correlation between sulphur contents, ash yields (and GWI) and GI values as the indicators which themselves alone show more or less expressed trends, can be interpreted as the consequence of not only one but of several types of processes. For example, the positive correlation between ash yield and sulphur content can be regarded as the consequence of inflowing mineral matter which caused more alkaline conditions and thus enhanced bacterial activity responsible for sulphur (either inorganically or organically bound) enrichment. But, on the other hand, where no correlation between mineral matter and sulphur content was ascertained, the latter could be more influenced by e.g. dry/wet conditions. In waterlogged wet conditions, (not reflected by GWI because GWI is mostly defined by clastic inorganic matter), sulphur content due to increased alkalinity can rise because alkalinity is enhanced by stagnant and calm open-water environment within an alkaline, e.g. carbonate-rich regional geological realm.

As a general conclusion to the above debate it can be summarized that the tectonically intermountain realm of the young lignite formation – as the Velenje basin is – can be responsible for petrographic and bulk geochemical irregularities, as discussed above. On the contrary, in the paralic coal-forming settings, which are paleo-geographically much wider than the intermountain basins, also correlations between the facies indicators are expected to be more regular than in the case of locally highly tectonically, lithologically and climatologically influenced intermountain basins.

#### 6.4.1.4.4. Paleo-environmental interpretation based on DIESSEL's (1986) facies diagrams

In the systematic study of the Velenje lignite presented in this monograph, it was for the first time in Slovenia that DIESSEL's (1986) facies diagrams were used for the interpretation of paleo-environments being responsible for coal formation. The results for separate units are presented in **Fig. 6.61**. The first three diagrams – **a)**, **b)** and **c)** – explain paleo-environments being responsible for lignite formation throughout the P-9k/92 lignite profile, and the **d)** diagram describes the paleo-environment for the P-8z/92 lignite profile.

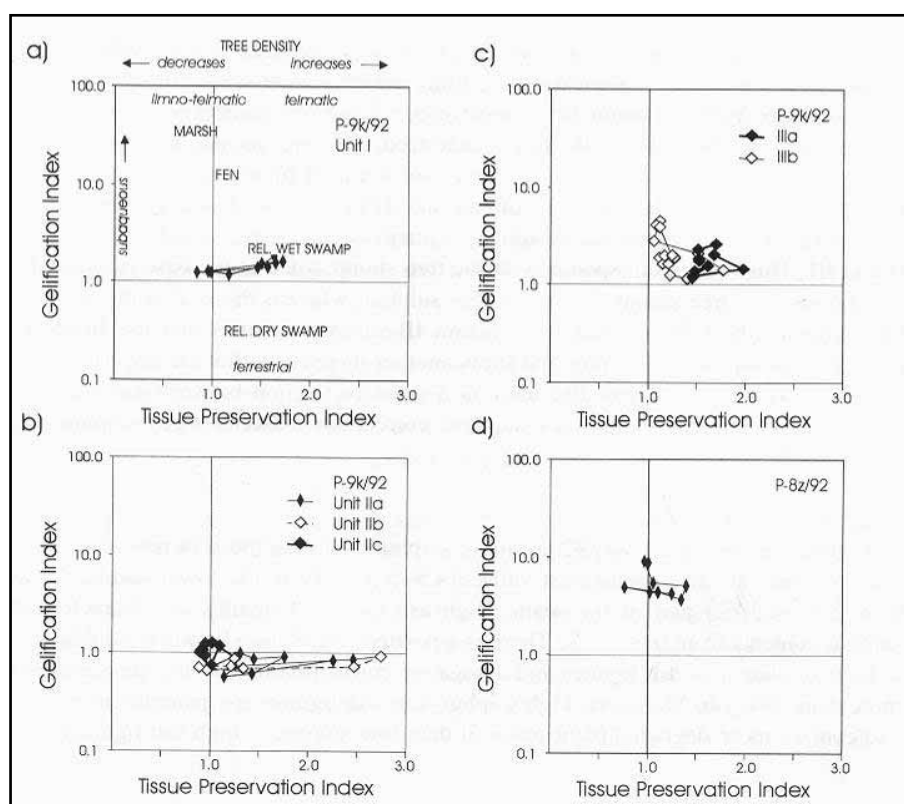
In borehole P-9k/92, the relatively wet forest swamp characterizes the lowermost (**unit I**) part of the lignite seam (**Fig. 6.61-a**). This fact corresponds well to the megascopic description,

which expresses that the xylite-rich lignite with clastic input builds up this initially formed sequence of the Velenje lignite.

In **unit II** in the P-9k/92 profile, the TPI varies widely in subunits II-a and II-b, and the GI is lower than in the underlying unit I. These facts indicate drier tree-forest conditions with highly variable conditions for biochemical gelification (early diagenesis) of the biomass available. In subunit II-c, the GI/TPI ratio uniforms, and this can be an indication of uniformity of both the biochemical processes and vegetation pattern. Bush moor, with moderately resistant plant communities and with moderate water-logging can be a good explanation for these petrographic effects.

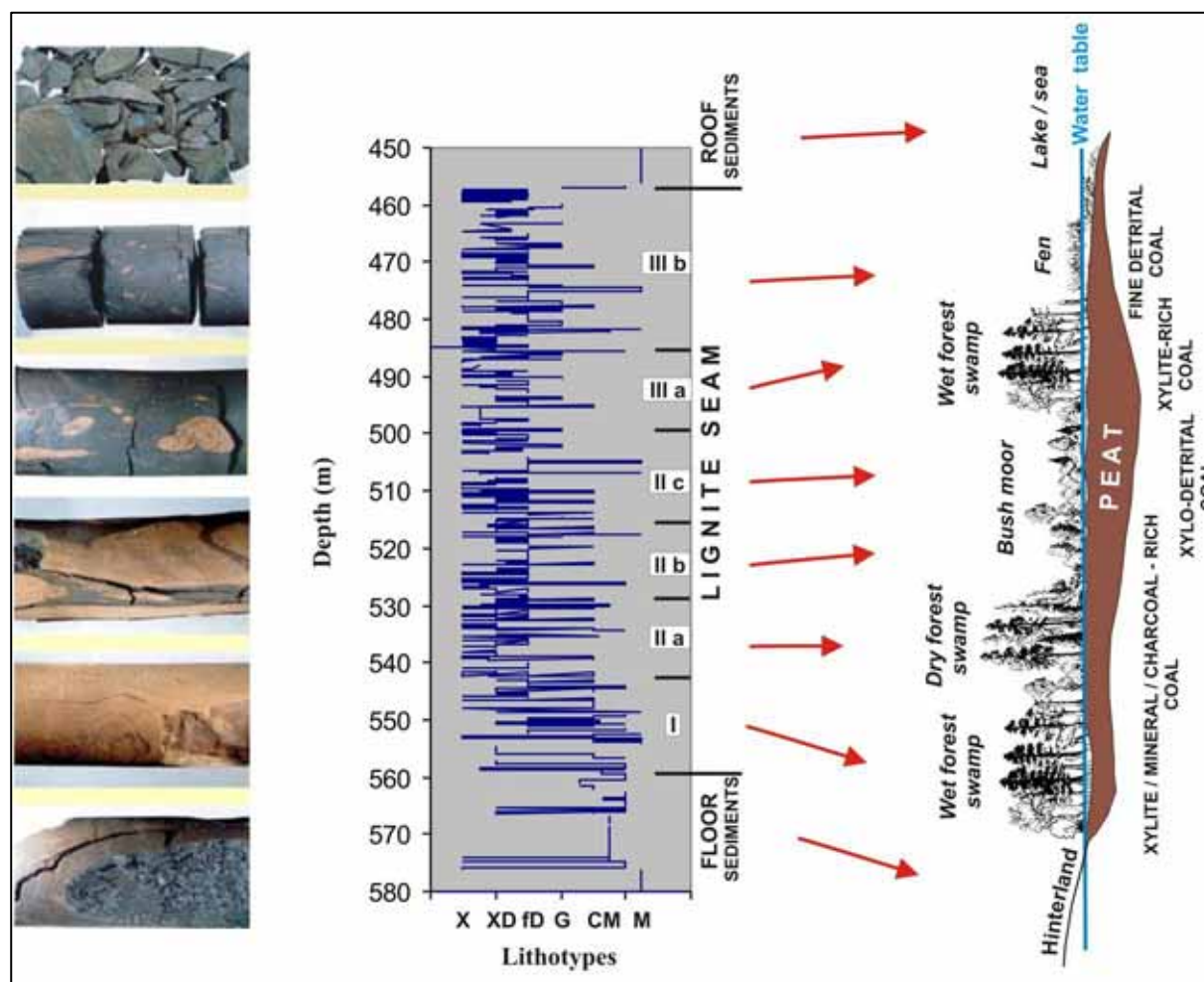
An increased GI and TPI in **subunit III-a** can be interpreted as an establishment of wet forest environment again. In contrast to the wet forest swamp environment in unit I, this forest swamp is much purer in regard to the mineral matter influx. Due to alkaline water-logging, it is moderately sulphur-rich. In **subunit III-b**, the microscopically defined gelification index (GI) increases significantly, TPI is uniform, and the fine-detrital, partially gelified lignite is the prevailing lithotype. All these features can be clearly explained as the fen environment, increasingly subaqueous, which led to the formation of the uppermost part of the lignite seam in the central part of the Velenje peat-forming basin.

In the P-8z/92 lignite profile, the relatively high GI and the low, not very variable TPI indicate an environment between wet forest swamp and fen. High GI values and high sulphur contents support an interpretation of a water-logged and alkaline environment of the peat-forming environment giving rise to lignite at the site of borehole P-8z/92.



**Fig. 6.61:** Coal facies diagrams as proposed by DIESSEL (1986) – with values for the Velenje lignite. Diagrams a), b) and c) present GI/TPI values for units I, II and III from the P-9k/92 lignite core profile. Diagram d) shows GI/TPI values for lignite from the P-8z/92 core profile. (From MARKIČ & SACHSENHOFER, 1997).

Several models of peat-forming environments are published in the literature. To illustrate a peat-forming environment as achieved by DIESSEL's facies diagrams (**Fig. 6.61**), a well known model by TEICHMÜLLER, M. (1958, 1989) can be applied also for the Velenje lignite as shown in **Fig. 6.62**.

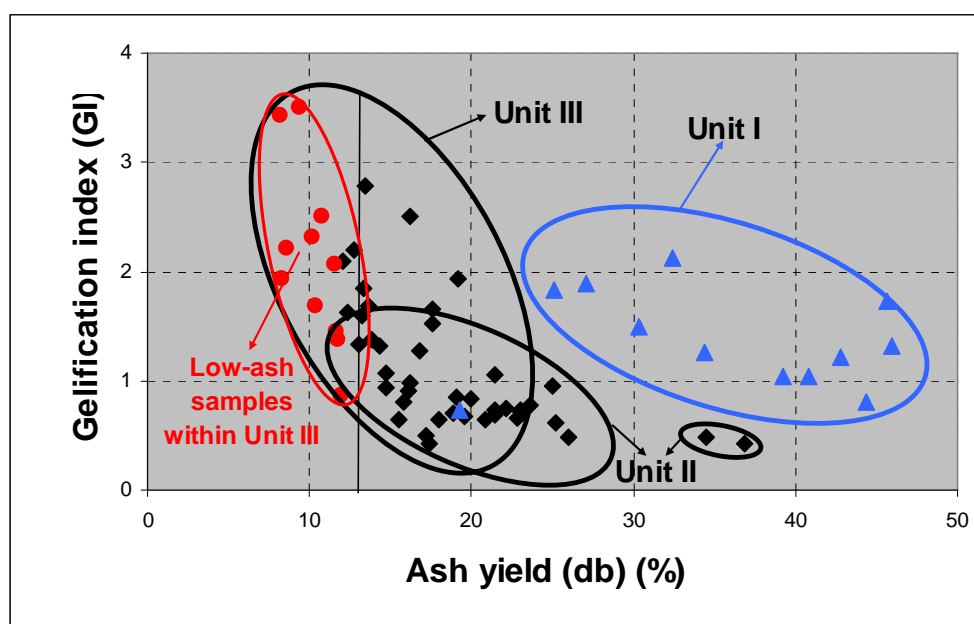


**Fig. 6.62:** Lithotype curve of the P-9k/92 lignite profile (analogous to that in **Fig. 6.46**), petrographic division into units I to III-b (from MARKIĆ & SACHSENHOFER, 1997), and reference to the peat-forming environments in a classical model by TEICHMÜLLER, M. (1958, 1989). Basic lithotype varieties (from **Fig. 6.3**) are shown on the left side.

#### 6.4.1.4.5. Relationship between the ash yield and the gelification index

In addition to DIESSEL's (1986) diagrams, the relationship between the ash yield and the gelification index will be discussed here because adventitious mineral matter reflects wet versus dry conditions as well as it also characterizes the geochemistry of water soaking the biomass. A diagram showing the gelification index (GI) versus the ash yield for samples from borehole P-9k/92 is given in **Fig. 6.63** and for samples from borehole P-8z/92 in **Fig. 6.64**. Source data for the P-9k/92 profile are from **Tab. 6.14**, whereas for the P-8z/92 profile, they are from **Tab 6.15**.

As evident from **Fig. 6.63**, GI drops very rapidly from ca 3.5 to 1.0 within a range of lignite samples yielding less than 12 % ash<sup>30</sup> (red dots). The next outstanding trend, relating to units II and III, is an exponential-like decrease of GI with an increasing ash yield. This relation is quite expected because non-gelified and inertinitic macerals, which diminish the GI, are mostly connected with environments of relatively higher energy and hence more or less considerable fluvial mineral matter influx, whereas the gelification proceeds better in calm-water low-lying peat-forming environments with a restricted to negligible mineral matter influx. However, in unit I, the lignite is relatively more gelified in respect to its mineral matter (ash) content than in the upper units. Since unit I is interpreted as the wet forest swamp (**Figs. 6.61** and **6.62**), water-logging itself, minerotrophy and considerable bacterial activity probably played a relatively more pronounced role than in the overlying unit II interpreted as the dry forest swamp and bush moor. Slight alkalinity, which was – as evidenced from geochemical data (**Chap. 8.5.1**) – undoubtedly a significant factor of biochemical gelification in the upper part of the seam, was not outstanding in the lower part of the seam. On the contrary, highly predominating alumo-siliceous clayey mineral matter in unit I made this environment relatively acid. Acidity is well known to inhibit the biochemical degradation of



**Fig. 6.63:** Relations between the ash yield (on the dry basis) and the gelification degree (expressed by GI) based on samples from the P-9k/92 lignite seam profile.

plant material, whereas alkalinity is known to enhance it. But, on the other side, BECHTEL et al. (2003) found out that cellulose yield of the Gymnosperm fossil woods is typically lower (ca 11 %) in the lower part of the seam in comparison to the upper part where it ranges up to 36 %. Our observations that gelified xylite (gelo-xylite) is frequently encountered in the lower part of the seam confirm the previously mentioned fact of high plant decomposition as indicated by the loss of cellulose. BECHTEL et al. (2003) attributed low cellulose yield to the activity of fungi and bacteria under aerobic conditions. Aerobic fungal and bacterial activity

<sup>30</sup> Less than 12 % ash yielding lignite is considered in this monograph as the low-ash lignite which is suitable for coal rank evaluation – see **Chap. 7.2**.

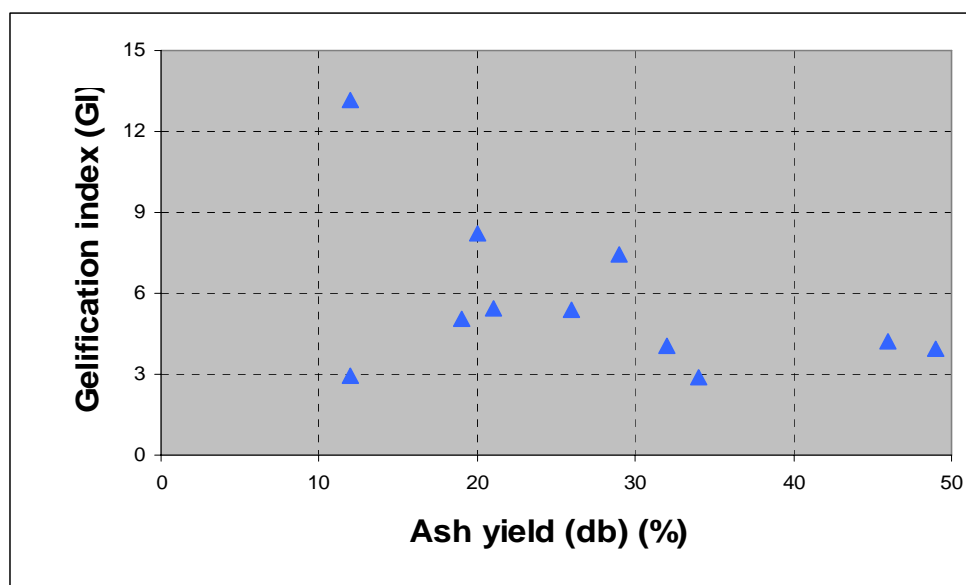


in unit I could therefore play some role also in the gelification process, especially in the phase when the peat accumulation had characteristics of acrotelm, but the rise in the intensity of the gelification process was most probably achieved when the water table raised and caused the pre-existing peat accumulation to become a waterlogged catotelm. In catotelm, only anaerobic bacteria are active, mostly governing the biochemical gelification process.

The petrography of lignite in unit II (and its subunits) reflects dryer conditions and lower mineral influx than lignite in unit I. The lowest gelification of unit II ( $<1.5$ ) can be clearly interpreted as the consequence of relatively dry conditions (low bacterial activity) and acidity.

The uppermost part of the seam developed from the wet forest swamp (unit III-a) and finally from the fen vegetation (**Figs. 6.61** and **6.62**). The acrotelm zone is expected to be reduced on the account of catotelm. Prevailing anaerobic bacteria are presumed to act in the upper part of the seam (BECHTEL et al., 2003), characterized by low mineral matter content, relatively higher Ca content in the inorganic fraction and hence more alkaline milieu of biomass humification and biochemical gelification. From all these reasons, the uppermost part of the seam is in general the most gelified (**Fig. 6.60**). Very interestingly, lignite samples whose mineral matter was geochemically analyzed as outstandingly Ca-rich (samples 68, 72, 73, 90, and 92 – all low-ash samples; **Tab. 8.6, Fig. 8.3**), also exhibit the highest gelification degrees (GI mostly  $>2$ ).

A considerably higher gelification than in the P-9k/92 lignite seam profile was ascertained in the P-8z/92 profile (**Fig. 6.64**) – even though the lignite in P-8z/92 is generally more ash yielding. This is clear evidence that the carbonate rocks occurring to the north of the basin and close beneath the lignite seam gave an outstandingly alkaline character to the biomass-soaking water.



**Fig. 6.64:** Relation between ash yield (on the dry basis) and gelification degree (expressed by GI) based on samples from the P-8z/92 lignite seam profile. Gelification indices reflect a significantly stronger gelification in this profile than in P-9k/92 in **Fig. 6.63**.

## 7. COAL RANK ESTIMATION OF THE VELENJE LIGNITE

The coal rank of the Velenje lignite will be estimated in this chapter by all rank parameters that are used as rank indicators in most “national” rank classifications as well as in the newest ECE-UN (1998) In Seam Coal Classification. Among the national classifications, the German (also termed DIN) and the USA (also termed ASTM) system are presented together with the ECE-UN (1998) classification in **Fig. 7.1**. Both national classifications are based exclusively on rank boundaries, whereas the ECE-UN classification takes into account also the petrographic composition and the ratio between organic and inorganic part expressed by the ash yield. In **Fig. 7.1**, only the “rank part” of the ECE-UN classification is shown, whereas the complete ECE-UN classification, in which also the Velenje lignite is placed by its bulk rank, grade and petrographic characteristics (derived from data in **Tab. 2.2** – Facts about the lignite seam), is shown in **Fig. 7.2**. Ranging of the Velenje lignite as characterized more precisely by different rank parameters is shown in **Fig. 7.5**.

Rank classifications			Refl. %	Vol.M d.a.f. %	Carbon d.a.f. Vitrain	Bed Moisture %	GCV MJ/kg m.a.f. (d.a.f.)	Applicability of different rank parameters (simplified after Stach et al., 1982)
ECE-UN	German	USA						
LOW - RANK								
PEAT	Torf	PEAT	0.2	68				
				64	ca 60	ca 75		
Ortho-LIGNITE (15/28)	Weichbraunkohle (Soft brown coal)	Lignite	0.3	60				
Meta-LIGNITE (26/30)	Matt (Dull)			56		ca 35	16,744 (28,7)	
Sub-BITUMINOUS COAL (24/31)	Haftbraunkohle (Hard brown coal)	Sub-Bit	0.4	52				
		C		48	ca 71	ca 25	23,023 (30,8)	
		B						
		A		44	ca 77	ca 19	29,302 (33,0)	
MEDIUM - RANK								
		B	0.5	40				
		A	0.6	36				
		High Vol. Bituminous	1.0	32				
		Medium Volatile Bituminous	1.2	28	ca 87		36,309	
		Low Volatile Bituminous	1.4	24				
			1.6	20				
			1.8	16				
HIGH - RANK								
		Semi-Anthracite	2.0	12				
		Anthracite	3.0	8	ca 91		36,309	
		Anthracite	4.0	4				

**Fig. 7.1:** The German and the USA national coal rank classifications (from STACH et al., 1982) in comparison to the ECE-UN (1998) classification – for ranging of the Velenje lignite see **Fig 7.5**.

Abbreviations are the following:

Refl. – huminite reflectance in oil

Vol.M – volatile matter

GCV – gross calorific value

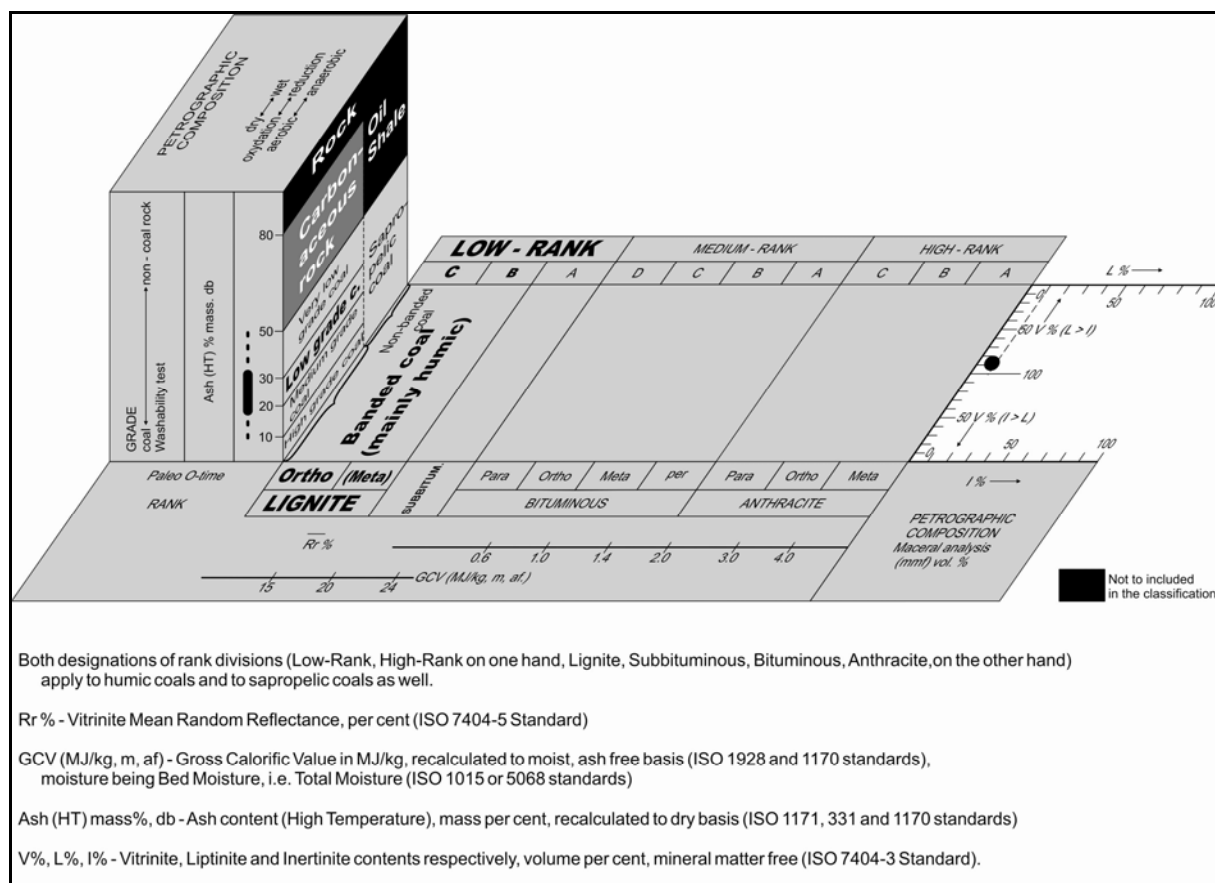
d.a.f. – dry, ash-free basis

m.a.f. – moist, ash-free basis

The GCVs are given at the moist, ash-free basis (maf) and at the dry, ash-free basis (daf), respectively. The latter values are cited in brackets. GCVs are cited as delimiting values between rank coals in the ECE-UN (1998) classification. Note also the applicability of different rank parameters for different coal ranks. The ECE-UN (1998) classification is mostly based on the so called Alpern Coal Classification (ALPERN et al., 1989).

The ECE-UN (1998) In-Seam Coal Classification was developed by the Group of Experts on the Utilisation and Preparation of Solid Fuels (ECE-CSE-UN ENERGY/1998/19 document) at

the ECE-CSE-UN<sup>31</sup> Working party on Coal. It represents the newest international coal classification scheme. It was realised mainly with the aim to unify coal classes from the national classifications<sup>32</sup>, and, as already mentioned, to broaden the classification criteria not only to rank parameters but also to petrographic composition and grade (ash yield). The ECE-UN (1998) classification is mainly based on the work of ALPERN et al. (1989) and was also termed the Alpern Coal Classification.



**Fig. 7.2:** General version of the ECE-UN (1998) In-Seam Coal Classification (copied and rewritten from the ECE-CSE-UN ENERGY/1998/19 document). The Velenje lignite is characterized by values and designations for grade, rank and petrographic composition as accented in bold black (see further text for more explanation).

The German and the USA classifications are taken into consideration in this monograph because terms and criteria from both of them were (and still are) mostly used for coals in Slovenia. Namely, from the very beginning of coal mining at the end of the 18<sup>th</sup> century onwards, the so called “hard brown coals”, mainly of the Oligocene age, have played an important role. They were termed as the “Hartbraunkohlen”, divided into “Mattbraunkohle” (“dull brown coal”) and “Glanzbraunkohle” (“bright brown coal”) subclasses, as defined in the German national classification. On the other hand, the German term “Weichbraunkohle”, i.e. “soft brown coal”, never found the use in Slovenian terminology. Instead, the term “lignite” was used already in the 19<sup>th</sup> century, also by the German speaking authors, as e.g. by

<sup>31</sup> ECE-CSE-UN: Economic Commission for Europe – Committee on Sustainable Energy – United Nations.

<sup>32</sup> Beside the German and the USA national classifications, the Russian, French and Australian are among the most widely used ones.

F. ROLLE as far back as in 1860. The situation was similar in the rest of the former (before 1991) Yugoslavia countries in which lignite production greatly prevailed (about 85 % of lignites versus 15 % of higher rank coals). One recent petrological overview of low-rank coals in Serbia was done by ERCEGOVAC et al. (2006). Our use of the term “lignite” refers to the lowest rank coals with very clearly visible brown pieces of xylitic fragments within darker fine-detrital groundmass (or matrix). The time of deposition and time of coalification of the Velenje lignite in comparison to coals in the Eastern Alps was discussed by SACHSENHOFER (2000).

In the continuation, the following parameters to evaluate the coal rank of the Velenje lignite will be discussed:

- Huminite reflectance,
- Moisture content,
- Calorific value,
- Volatile-matter and carbon contents.

As the thickness of the Velenje lignite seam ranges to only 100 m (extremely to 165 m), no significant trends in coal rank with depth are expected (although a slight decrease in moisture due to increasing overburden might be visible). Moreover there are no indications for rank disturbances caused by local temperature/pressure effects. However, rank-sensitive parameters may vary significantly due to the different sources of the organic material present in lignite (e.g. wood with different cellulose, lignin and resin contents), which is not yet homogenised in low rank coals. Moreover, the relatively high portion of mineral matter, especially in the lower part of the Velenje seam, influences some rank parameters.

In the argumentation to the Alpern Coal Classification (ALPERN et al., 1989) (later modified into the ECE-UN (1998) classification as shown in **Fig. 7.2**), the authors clearly discussed also the suitability and constraints of the use of different rank parameters – especially of the following:

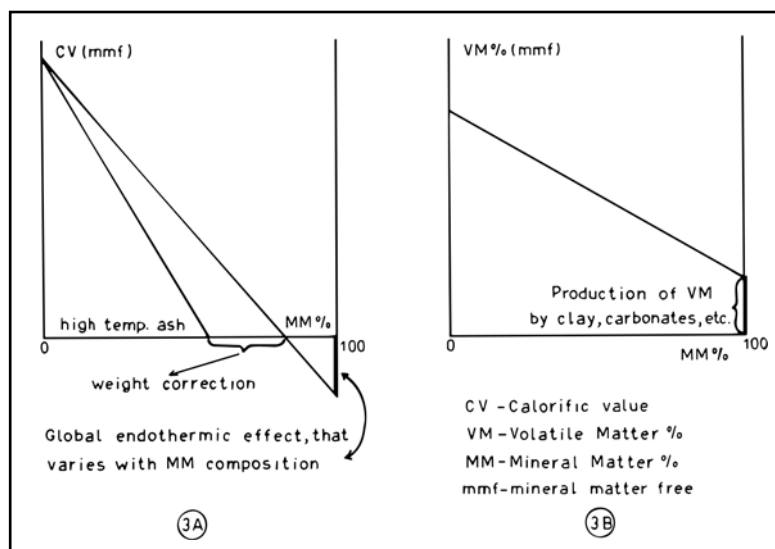
- Gross calorific value<sup>33</sup> at the moist, ash-free basis ( $GCV_{maf}$ ) calculated on the moisture holding capacity;
- Moisture holding capacity at the ash-free basis ( $MHC_{af}$ );
- Bed moisture at the ash-free basis ( $BM_{af}$ ); and
- Gross calorific value at the dry, ash-free basis ( $GCV_{daf}$ ).

Among these four, the  $MHC_{af}$  and the  $GCV_{maf}$  are the best two parameters to be used (ALPERN et al., 1989, p.10). Especially important in the ALPERN's et al. (1998) contribution in regard to the Velenje lignite is the pointing out that the mineral matter (ash yield) considerably influences the calorific value as analyzed in the bomb combustion calorimeter (ISO 1928) due to thermal decomposition of minerals. Schematic relations between the decreases of rank values (calorific value – CV, and volatile-matter content – VM) and mineral matter contents are shown in **Fig. 7.3** copied from ALPERN et al. (1989, p.8).

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<sup>33</sup> In the original paper of ALPERN et al. (1989) only “calorific value” is used. From the context of the paper and in comparison to the ECE-UN (1998) classification it is evident that the calorific value of ALPERN et al. (1989) is the “gross calorific value”.

For the reasons cited above, “pure” coal samples are strictly recommended to be analyzed when coal rank is to be evaluated (and not any coals recalculated to the *maf* and *daf* bases, respectively). Due to mineral matter thermal effects (mostly endothermic, but in the case of oxidation of pyrite also exothermic – ALPERN et al. (1989, p.8)) and also due to specific properties of macerals (e.g. suppressed huminite reflectance due to lipid substances), discrepancies in rank evaluation of coals on the basis of different rank parameters can occur as interestingly discussed e.g. by CORRÊA DA SILVA (1989) for the mineral-rich hyp-autochthonous Gondwana coals. Mostly it is suggested that, carbon and volatile matter should not be used in the rank parameters if ash yield exceeds 10 %. The 10 % ash yield limit between “pure” and higher ash coals is also mentioned by ALPERN et al. (1989, p.4).



**Fig. 7.3:** Consequences of mineral thermal decomposition for the calorific value (3A) and volatile-matter content (3B), when calculated on a mineral-matter-free basis. The graphs are only schematic – copied from ALPERN et al., 1989, p.8). (Mineral-matter-free basis for CV and VM can be approximately regarded as the ash-free basis.)

An important aspect of rank evaluation is that different rank parameters are differently applicable for coals of different ranks. For lignites, according to all three classifications in **Fig. 7.1** (and **Fig. 7.2**), the best applicable rank parameter is the calorific value, more precisely, the gross calorific value (GCV). Especially recommended is its use at the moist, ash-free basis ( $GCV_{maf}$ ), moisture being the bed moisture (or, even better, moisture from moisture holding capacity) – and! - the coal analyzed should be as “pure” as possible, with ash yields of less than 10 weight % at the most. If bed moisture is not well established – e.g. in cases of core sampling carried out after the coal had been exposed to the air for a considerable time – then, by taking into account the so called “as-received” moisture content, GCV can be expressed at the dry, ash-free basis ( $GCV_{daf}$ ). This approach – although it is not recommended by ALPERN et al. (1989), but acceptable by the “national classifications” – was for example recently used by MARKIČ et al. (2007) in the rank evaluation of mostly “whole” coals in Slovenia based on data from very different sources and time periods.

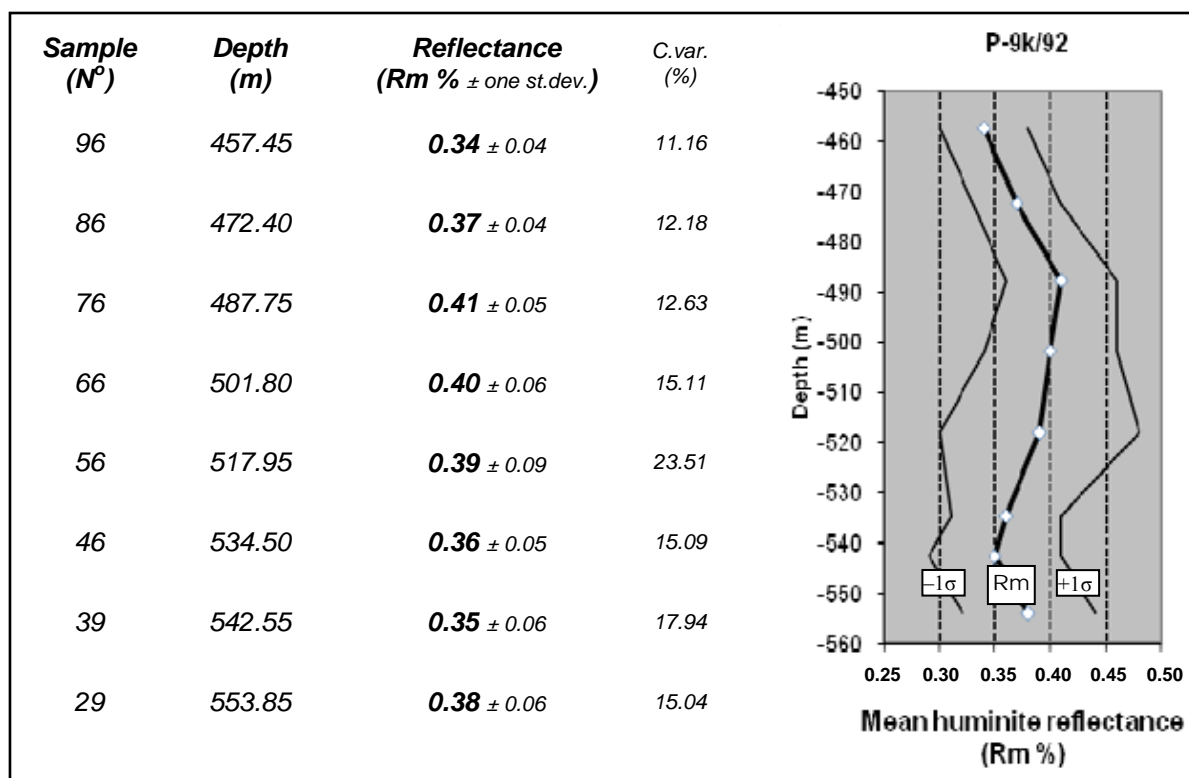
Most rank-indicating parameters are available for the Velenje lignite. Only data on the moisture holding capacity are missing, because this parameter is not routinely analyzed in the coal labs in Slovenia.



Rank evaluation will start with huminite reflectance, which was analyzed only on few samples and can thus maybe serve as a suitable introduction to the rank debate on larger sets of samples, analyzed by other rank parameters.

### 7.1. Rank determination by huminite reflectance

Huminite reflectance of the Velenje lignite was measured by HAMRLA (1985/86) and, in 1995, by the authors of this monograph. HAMRLA (1985/86) measured only one sample from the Preloge sector of the underground mine workings. He got the average value of 0.24 % for the mean huminite reflectance ( $R_m$ ) in oil, but he did not indicate in his paper what the exact huminite maceral that he measured was. In the second case, we measured eight petrographic samples from borehole P-9k/92 (see table in **Fig. 7.4**). These measurements were done at the Institute for Geosciences in Leoben (Austria) according to procedures as recommended in STACH et al. (1982) and in BUSTIN et al. (1985). The measured maceral variety was eu-luminite B. The reflectance in oil was measured in 50 points per polished block. The mean reflectance ( $R_m$ ) was defined by calculating the mean value of the 50 readings. As seen from **Fig. 7.4**,  $R_m$  values vary between 0.34 % and 0.41 %, with a mean reflectance value of about 0.37 %, with  $\pm$  one standard deviation between 0.04 and 0.09, i.e. with coefficient of variation (C.var.) between 11 % and almost 24 %.



**Fig. 7.4:** Mean huminite reflectance ( $R_m$ ) data (in oil) (with  $\pm$  one standard deviation ( $\sigma$ ) and coefficient of variation (C.var.)) for eight samples (polished blocks) from the P-9k/92 lignite core profile (left) and variation with depth (right). Notable is decrease of reflectance variability in the upper part of the seam (units III-a and III-b).

The observed variability in reflectance does not reflect differences in rank, but is a consequence of chemical variations. It is well known that darker or “A” varieties of huminite

macerals (see textinite A, texto-ulminite A etc. in **Tabs. 6.14** and **6.15**) contain slightly more hydrogen than brighter “B” varieties. Moreover, subtle oxydation (e.g. in the sense of the DIESSEL's (1992) fusinitization path of coalification) can increase the reflectance. Therefore, although the same maceral variety – eu-ulminite B – was chosen for the measurements, the effects of above cited factors most probably played some role. Reflectance values do not correlate with any of the parameters presented in **Fig. 6.60**, nor do they show any specialties in maceral composition. The only exception is sample 66, which is characterized by a relatively high reflectivity and a high content in degradofusinite (7 %) (**Tab. 6.14**).

The reflectance interval of 0.34 % to 0.41 % R<sub>m</sub> in samples from borehole P-9k/92 is shown in the classification in **Fig. 7.5**. This reflectance interval characterizes the lignite samples as meta-lignite. This rank is higher than that suggested by other parameters. However, it has to be emphasized, that huminite reflectance is not considered as an applicable rank parameter for low rank coals (see also **Figs. 7.1** and **7.2**)! The overestimated rank may be due to subtle oxydation of the Velenje lignite caused by pronounced aerobic bacterial and fungal activity during peatification. Slight oxydation is also supported by the fact that the Velenje lignite lithotypes are characterized by somewhat lower H/C atomic ratios than other coals in Slovenia (**Fig. 6.15**) (MARKIČ et al., 2007).

## 7.2. Rank determination by the moisture content, gross calorific value, and the volatile matter and carbon contents

The rank parameters cited in the title of this chapter will be treated jointly, because they are most commonly also analyzed and reported together. Each parameter will be discussed in short. The ranging of the Velenje lignite into the coal rank classification(s) (**Fig. 7.1**) on the basis of all representative rank-indicating values is presented in **Fig. 7.5**. It should be noted here that different sets and types of samples were used in this essay for a complex rank evaluation.

### 7.2.1. Moisture content

The moisture content can be used as the rank parameter if sampled and analyzed as the bed moisture (BM) and expressed on the ash-free basis (BM<sub>af</sub>) (**Fig. 7.1**) (ALPERN et al., 1989). In Velenje, the best data for bed moisture are those obtained through a systematic sampling for geomechanical investigations, which need strictly intact samples. According to the information of the geological service at the mine, bed moisture of the intact lignite samples amounts to ca 35 % at the as-received basis (*arb*). Another orientation datum, based on a very large sample set, is that from VEBER (1999) (**Tab. 2.2**), reporting that the average moisture content of the Velenje lignite is 30 % (*arb*). Taking into account both values and the average ash yield of about 22 % (*arb*) the bed moisture can be estimated to 38–45 %<sup>34</sup> at the ash-free basis. The most realistic rank designation for this BM value is the “soft brown coal” or “Weichbraunkohle” according to the German classification. Regarding the ECE-UN system, lignite with the mentioned moisture content interval of 38–45 % fits to the transition from ortho- to meta-lignite rank. It is assumed that the higher bed moisture value of 45 % (based on geomechanical samples) is more realistic than the lower one at 38 %. Bed moisture of even

<sup>34</sup> Value 38 % is calculated from 30/(100-22) and value 45 % is calculated from 35/(100-22).

“purer” lignite (with less than 10 % ash) is expected to be even somewhat higher than 45 %. Based on bed moisture, the Velenje lignite as a whole is thus classified into the ortho-lignite coal rank (**Fig. 7.5**).

### 7.2.2. Gross calorific value (GCV)

Apart from moisture, the gross calorific value at the bed-moist, ash-free basis ( $GCV_{bmaf}$ )<sup>35</sup> is the best rank parameter for low rank coals (**Fig. 7.2**).

The calorific value of different lithotypes of Velenje lignite with low ash yields (< 10 %, *db*) was analyzed by MARKIČ et al. (2007) (reference “b” in **Tab. 6.5**) involving samples from a “horizontal” underground borehole JV 768-H/98 drilled near the top of the lignite seam in the Preloge sector. Additional data are from borehole P-9k/92 (**Tab. 7.1**)<sup>36</sup> representing a vertical profile of the lignite seam (see **Chap. 6.4** and sub-chapters for petrographic data). Most samples yielded more than 10 % ash (*db*). Samples with less than 12 % ash yield are highlighted in **Tab. 7.1** (in light gray). Only these “low-ash” samples have been taken into account for rank evaluation. The 12 percent criterion (instead of the 10 % one) was applied to attain a slightly larger number of samples.

None of the analyzed samples contained the original bed moisture. Therefore, for rank evaluation  $GCV_{bmaf}$  was calculated considering original bed moisture of 45 %. Less-than-12-% ash samples with 45 % bed moisture are characterized by calculated  $GCV_{bmaf}$  values between 13.454 and 13.977 MJ/kg, with an average value at 13.700 MJ/kg. If the calculation is made at 40 % bed moisture then the  $GCV_{bmaf}$  varies between 14.677 and 15.247 MJ/kg, whereas the  $GCV_{bmaf}$  at 50 % bed moisture varies between 12.231 and 12.706 MJ/kg. The entire interval of these values (12.231 – 15.247 MJ/kg), ranges the lignite from borehole P-9k/92 into the ortho-lignite rank (**Fig. 7.5**).

**Fig. 7.5** also cites the  $GCV_{daf}$  values (in brackets) for lithotypes from **Tab. 6.5**. Xylite exhibits the lowest (24.050 MJ/kg) and the gelified fine-detrital lignite the highest  $GCV_{daf}$  values (26.420 MJ/kg). If 26.157 MJ/kg is considered as a (geometrically calculated) mean  $GCV_{daf}$  for detrital lignite, the  $GCV_{bmaf}$  at 45 % bed moisture reaches 14.386 MJ/kg. This rank estimation is well comparable to that cited for the low-ash samples from borehole P-9k/92 (**Fig. 7.5**).

The correlation between the  $GCV_{bmaf}$  and the  $GCV_{daf}$  is shown in **Fig. 7.6**. In black, the correlation published by ALPERN et al. (1989) is shown. It is based on 111 “world” samples, and exhibits close correlation particularly for the higher rank coals, whereas for the lower rank coals data are considerably alienated from the correlation line. In green, the delimiting

<sup>35</sup> *maf* and *bmaf* are both bases, which tell us that a coal's analytical datum or value is considered as moisture containing. If not specified precisely it can be ambiguous which moisture exactly is meant (moisture of partially dried coal, moisture obtained from a moisture holding capacity test, or real in-bed moisture). Mostly *m* refers to bed moisture. In order to be very clear, we introduced for bed moisture an abbreviation *bm*.

<sup>36</sup> *Cdaf* in **Tab 7.1** refers to the total carbon content (*Ctot*) - i.e. in both the inorganic (e.g. bound in carbonates) and organic form. In the rank evaluations, only the organic carbon (*Corgdaf*) is taken into account. Since the portion of inorganic carbon is negligible in macroscopically pure lignite samples (see **Tab. 8.1**, **Chap. 8.5.1**, and **Fig. 8.3**), the total carbon (*Ctot*) can be regarded as almost equal to the organic carbon (*Corg*). Hence, in our case, *Ctotdaf* can serve as an acceptable coal rank parameter.

values (16.744 and 28.700 MJ/kg, respectively) are shown for an (approximate) separation between the soft and the hard brown coal ranks. Red indicates the representative values (low-ash or <12 % ash coals only) for the Velenje lignite. It can be concluded that the  $GCV_{daf}$  versus  $GCV_{bmaf}$  ratios for the Velenje lignite do not fit well to the correlation line for the “world-coals”. Thermal effects at calorific value measurements due to a considerable mineral matter content (see **Fig. 7.3**) of the Velenje lignite (even though only samples with less than 12% ash yield were taken into account) may be an explanation for this fact. Moreover, also in the case of the ALPERN's et al. (1989) set of data, the lowest calorific value coals are characterized by the  $GCV_{daf}$  /  $GCV_{bmaf}$  values typically below the correlation line.

**Tab. 7.1:** Moisture and total carbon ( $C_{tot}$ ) contents, ash yields and gross calorific values ( $GCV_{daf}$ ) of lignite samples from borehole P-9k/92 (Unit III) as analyzed and reported at different bases (see abbreviations below), and  $C_{tot}$  contents and GCVs recalculated to relevant bases in order to be used as coal rank indicators. Gelification index values (GI) are added from **Tab. 6.14** as a petrographic indicator. Bed moisture (BM) is considered to be 45 weight %. Abbreviations for the bases of the reported data are as follows: arb – as-received basis; db – dry basis; daf – dry, ash-free basis; maf – moist, ash-free basis; bmaf – bed moist, ash-free basis. Low-ash (<12% db) samples are marked light gray.

Smp. (N°)	Unit	Depth (m)	<i>Analytical data</i>				$C_{tot}$ (daf) (wt. %)	GCV (maf) (MJ/kg)	GI	GCV (bmaf) 45% bm (MJ/kg)	GCV (bmaf) 50% bm (MJ/kg)
			Moist (arb) (wt. %)	Ash (db) (wt. %)	$C_{tot}$ (db) (wt. %)	GCV (daf) (MJ/kg)					
96	Unit III b	456.9	22.45	11.80	57.23	25.301	64.89	19.05	1.38	13.916	12.651
95		458.0	21.84	17.21	50.71	23.411	61.25	17.50	0.50	12.876	11.706
94		459.0	24.30	10.85	56.90	24.490	63.83	18.01		13.470	12.245
93		460.1	28.67	10.15	58.62	24.989	65.24	17.27	2.32	13.744	12.495
92		461.4	28.68	8.20	60.92	25.048	66.36	17.42	3.43	13.776	12.524
91		463.3	31.52	13.43	56.34	24.540	65.08	16.02	2.79	13.497	12.270
90		465.2	25.26	7.38	58.08	25.412	62.71	18.62	7.36	13.977	12.706
89		466.5	25.57	12.08	53.81	24.417	61.20	17.56	2.10	13.429	12.209
88		468.0	28.62	12.72	53.81	24.047	61.65	16.48	2.20	13.226	12.024
87		470.3	23.90	13.59	52.32	24.102	60.55	17.68	1.68	13.256	12.051
86		471.7	24.11	17.60	48.72	23.161	59.13	16.72	1.53	12.739	11.581
		473.1									
85		473.4	27.04	16.23	52.05	24.071	62.13	16.69	2.50	13.239	12.036
84		474.4									
83		474.9	26.16	17.57	50.21	23.610	60.91	16.51	1.65	12.986	11.805
82		477.0	21.76	13.32	52.72	23.719	60.82	17.96	1.84	13.045	11.860
81		478.1	24.64	13.83	53.03	23.945	61.54	17.36	1.38	13.170	11.973
80		480.0	26.66	12.37	54.44	24.224	62.12	17.12	1.62	13.323	12.112
79		481.6	27.20	22.98	45.39	22.814	58.93	15.36	0.73	12.548	11.407
78		483.2	26.63	14.74	52.27	23.859	61.31	16.73	1.07	13.122	11.930
		484.9									
77	Unit III a	485.3	29.14	10.42	56.55	24.590	63.13	16.85	1.69	13.525	12.295
76		486.7	21.52	13.01	52.42	23.423	60.26	17.81	1.33	12.883	11.712
75		488.8	24.64	13.23	52.41	23.263	60.40	16.90	1.59	12.795	11.632
74		490.2	28.64	23.00	45.92	22.515	59.64	14.80	0.72	12.383	11.258
73		491.6	27.03	8.28	58.64	25.037	63.93	17.83	1.94	13.770	12.519
72		494.4	23.04	9.42	59.07	25.089	65.21	18.86	3.50	13.799	12.545
71		494.4	25.98	10.81	57.22	24.462	64.16	17.55	2.50	13.454	12.231
70		495.2	24.46	16.24	51.37	23.108	61.33	16.67	0.98	12.709	11.554
69		496.1	30.50	11.52	57.19	24.656	64.64	16.48	2.06	13.561	12.328
68		497.8	21.01	8.57	59.08	24.489	64.62	18.97	2.21	13.469	12.245
		499.0									

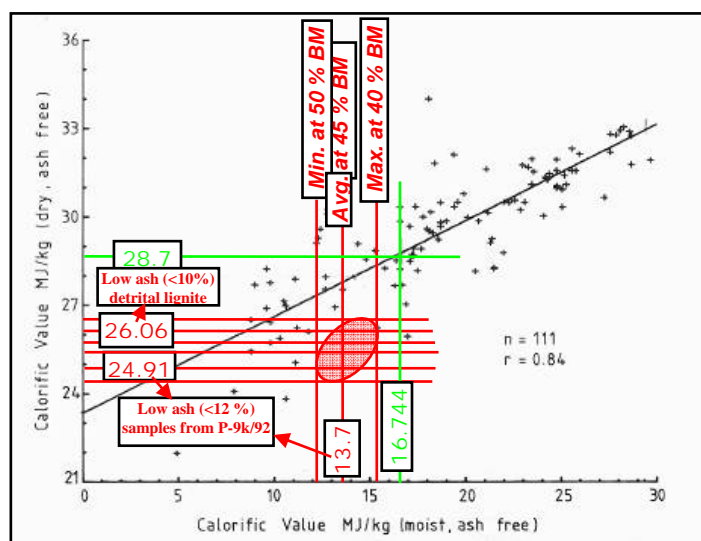
**Tab. 7.1** – Continuation

Smp. (N <sup>o</sup> )	Unit	Depth (m)	<i>Analytical data</i>				Ctot (daf) (wt. %)	GCV (maf) MJ/kg	GI	GCV (bmaf) 45% bm MJ/kg	GCV (bmaf) 50% bm MJ/kg
			Moist (arb) (wt. %)	Ash (db) (wt. %)	Ctot (db) (wt. %)	GCV (daf) MJ/kg					
67	Unit II c	499.3	24.04	16.11	50.89	23.100	60.66	16.77	0.91	12.705	11.550
66		501.0	16.98	12.00	57.45	25.402	65.28	20.61	0.86	13.971	12.701
65		502.6	21.77	11.64	56.19	24.849	63.59	18.90	1.45	13.667	12.425
64		504.1	21.60	21.49	49.05	23.863	62.48	17.66	0.73	13.125	11.932
63		505.9	21.74	22.83	46.96	23.414	60.85	17.22	0.66	12.878	11.707
62		507.5	21.46	15.50	53.63	24.593	63.47	18.58	0.65	13.526	12.297
		508.8									
61		509.2	23.89	14.70	50.86	24.322	59.62	17.78	0.94	13.377	12.161
60		510.8	17.65	19.15	48.82	24.505	60.38	19.37	1.94	13.478	12.253
59		512.7	17.64	19.06	48.92	24.000	60.44	18.98	0.85	13.200	12.000
		514.2									
58	Unit II b	514.6	21.44	21.49	47.03	23.883	59.90	17.72	1.05	13.136	11.942
57		516.2	23.60	22.10	44.71	23.016	57.39	16.48	0.74	12.659	11.508
56		517.3	23.65	15.84	51.93	24.981	61.70	18.26	0.81	13.740	12.491
55		518.6	22.14	25.17	43.86	23.601	58.61	17.10	0.61	12.981	11.801
54		519.8	23.68	18.83	50.12	24.516	61.75	17.74	0.71	13.484	12.258
53		522.0	22.50	18.02	49.59	24.256	60.49	17.91	0.65	13.341	12.128
52		523.5	18.70	21.46	47.01	23.974	59.85	18.54	0.69	13.186	11.987
51		525.4	18.37	19.92	47.86	24.109	59.77	18.82	0.84	13.260	12.055
50	Unit II a	527.0	20.47	16.81	49.05	23.733	58.96	18.13	1.28	13.053	11.867
49		528.7	18.87	34.53	37.06	22.003	56.61	16.24	0.49	12.102	11.002
48		530.4	22.59	17.41	49.82	24.265	60.32	17.93	0.43	13.346	12.133
47		532.0	19.69	23.62	46.17	23.934	60.45	18.12	0.78	13.164	11.967
46		533.6	19.64	20.88	47.79	23.833	60.40	18.21	0.64	13.108	11.917
45		535.4	18.43	14.35	55.31	25.090	64.58	19.85	1.32	13.800	12.545
44		536.5	18.51	19.52	51.06	25.073	63.44	19.55	0.67	13.790	12.537
43		537.8	21.08	24.97	46.66	24.254	62.19	17.89	0.95	13.340	12.127
42		539.0	19.35	25.98	45.98	24.088	62.12	18.19	0.48	13.248	12.044
41		540.5	20.73	36.84	38.66	23.613	61.21	16.70	0.43	12.987	11.807
40		541.5		58.22							
39	Unit I	542.1	23.71	19.24	49.35	23.841	61.11	17.22	0.73	13.113	11.921
38		543.0	26.06	32.39	40.08	22.903	59.28	15.05	2.12	12.597	11.452
37		543.9		64.59							
36		544.5	26.39	27.06	45.15	23.378	61.90	15.67	1.89	12.858	11.689
35		545.5	21.12	30.30	43.56	23.927	62.50	17.29	1.50	13.160	11.964
34		547.5		61.83							
33		547.7	22.77	44.37	32.93	21.822	59.19	14.26	0.81	12.002	10.911
32		549.2	15.79	42.74	33.61	21.859	58.70	16.47	1.21	12.022	10.930
31		550.7	16.32	45.67	32.45	22.225	59.73	16.35	1.73	12.224	11.113
30		552.0	28.77	25.08	48.05	23.798	64.14	15.46	1.83	13.089	11.899
29		553.2	27.20	39.26	35.16	21.237	57.89	13.15	1.04	11.680	10.619
28		554.5	26.24	34.40	39.31	21.854	59.92	14.17	1.26	12.020	10.927
27		555.8	23.50	45.95	31.55	21.237	58.37	13.54	1.32	11.680	10.619
26		557.0	25.31	40.82	34.32	20.931	57.99	13.31	1.04	11.512	10.466
		557.8									



Rank classifications			Ref.	Vol.M	Carbon	Bed	GCV	Applicability of different rank parameters (simplified after Stach et al., 1982)
ECE - UN	German	USA	R <sub>m-oil</sub>	d.a.f. %	d.a.f. Vitrain	Moisture %	MJ/kg m., a.f. (d.a.f.)	
LOW - RANK	PEAT	Torf	PEAT	0.2			(24.05) Xylite - X	
				0.24			(25.69)	
				0.3			(26.14)	
				0.34			(26.42)	
	Ortho-LIGNITE	Weich-braunkohle (Soft brown coal)	Lignite	0.3			12.231	
	Meta-LIGNITE			0.34			13.454	
				0.34			13.977	
				0.34			15.247	
				0.34			16.744	
				0.34			(28.7)	
	Sub-BITUMINOUS COAL	Matt (Dull)	Sub-Bit	0.4			23.023	
				0.41			(30.8)	
	Para -	Glanz (Brilliant)	C	0.5			29.302	
				0.6			(33.0)	
				0.7				

**Fig. 7.5:** Coal rank characterization of the Velenje lignite (in red values and intervals) within the rank classifications (see also Fig. 7.1). For the values and intervals see more explanation in the text.



**Fig. 7.6:** Correlation between GCVbmaf and GCVdaf based on 111 world coals from ALPERN et al. (1989) (in black), and representative GCVs for the Velenje lignite (in red). Bad fitting (red oval) of the Velenje values to the correlation line may be explained by thermal effects due to ash yield (see Fig. 7.3) in the Velenje lignite (even though only samples with less than 12% ash yield are taken into account). The lowest cited GCV boundary from the classification chart in Fig. 7.5 is signed in green. Note that also in the ALPERN's et al. (1989) set of data correlation is bad for low rank coals.

### 7.2.3. Volatile-matter and carbon contents

The volatile-matter (VM) and carbon (C) contents at the dry, ash-free basis (VM<sub>daf</sub>; C<sub>daf</sub>) (Fig. 7.1) are traditional rank parameters for hard coals. However, their applicability for low rank coals is limited. Moreover, the significance of VM<sub>daf</sub> and C<sub>daf</sub> values as a rank parameter is limited because both parameters depend on maceral composition.

VM<sub>daf</sub> data for the entire lignite seam can be taken from the reserves elaboration by VEBER (1999) and from VEBER & DERVARIČ (2004) (Tab. 2.2), according to which the average VM<sub>daf</sub> ranges from 57.7 to 58.3 %. Despite of the limitation of the VM<sub>daf</sub> approach for low rank coals, this interval corresponds well to the bed moisture content and the calorific value

and supports the classification of the Velenje lignite as “soft brown coal” at the transition between the ortho- and the meta-lignite rank (**Fig. 7.5**). Because the “entire coal from the whole basin” with an ash yield of 22 % (**Tab. 2.2**) is considered in the calculation of the  $VMdaf$  content from VEBER's data, the true  $VMdaf$  content is expected to be even somewhat higher, thus ranging into the ortho-lignite coal rank as well.

Carbon contents are available for different lithotypes from the Velenje lignite (**Tab. 6.5**) and for borehole P-9k/92 (**Tab. 7.1**). As pointed out in **Chap. 6.3.1.7**, xylite has the lowest carbon content (57.8 %  $C_{totdaf}$ ) among the lithotypes (**Tab. 6.5**), whereas  $C_{totdaf}$  values of xylite and fine-detrital (XD-fD) varieties of lignite range from 65.0 to 67.0 %  $C_{totdaf}$ . Similar percentages were found in samples from borehole P-9k/92 (**Tab. 7.1**), where  $C_{totdaf}$  values for samples with less than 12 % ash vary between 62.7 and 66.4 %. This range of the  $C_{totdaf}$  values, excluding xylite, agrees with a classification of the lignite samples into the ortho- and meta-lignite rank (**Fig. 7.5**).

### 7.3. Variation of the GCV $_{bmaf}$ throughout the P-9k/92 lignite seam profile

The variation of the GCV $_{bmaf}$  of all samples throughout the P-9k/92 lignite seam profile is shown in **Fig. 7.7-b**. For a comparison, logs of the ash yield ( $db$ ) and of the gelification index (GI) are added (**Figs. 7.7-a**, and **7.7-c**). The logs are based on data from **Tab. 7.1**. The three log lines in **Fig. 7.7-b** represent the variation of the GCV $_{bmaf}$  at three bed moisture “levels” – at 50 % (left curve), at 45 % (central curve in bold), and at 40 % (right curve). On the 45 % bed moisture curve, the low-ash (<12 %) samples from **Tab. 7.1** are pointed out by filled circle dots. It is very clearly evident that these samples (almost all in unit III) are characterized by the highest GCV $_{bmaf}$  values. Samples characterized also by high GCV $_{bmaf}$ , yielding between 12 and 20 % ash, are signed by empty circles. It is evident from **Fig. 7.7-b** that the GCV $_{bmaf}$  depends on the ash yield, (or, more precisely, on the mineral matter content). The reason is, as already discussed (**Fig. 7.3**), in endothermic reactions, which are more effective at a higher mineral matter content. The correlation between the GCV $_{bmaf}$  and the ash yield (**Fig. 7.8-a**) is characterized by  $r^2 = 0.68$  (or  $r = -0.82$ ). An explanation for a not closer correlation may be differences in mineralogical compositions of lignite samples with an approximately equal ash yield, as well as petrographic differences with respect to ratios between xylite and fine-detrital (matrix) lignite (**Fig. 7.8-c**).

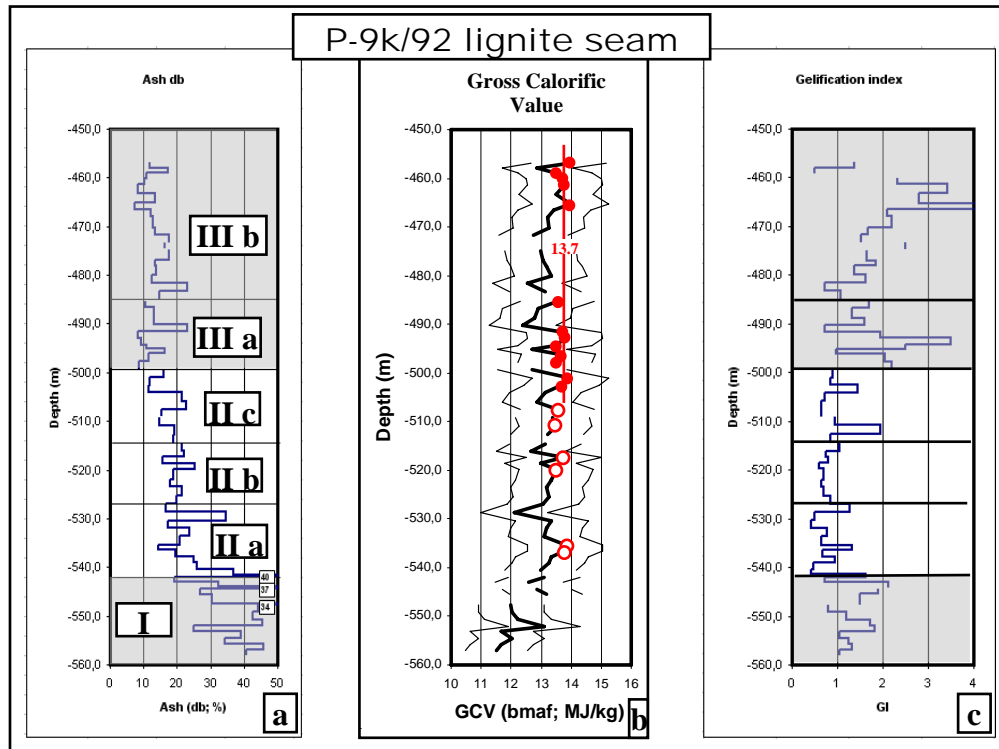
**Fig. 7.8-b** shows the relation between the GCV $_{bmaf}$  ( $bm$  being 45 %) and the gelification index (GI). The correlation for the entire set of data from the P-9k/92 profile is very weak ( $r^2 = 0.21$ ), however, there are interesting relations to the two lines defined by the equations:

$$y = 1.03 x + 10.2 \text{ which corresponds to: } GCV_{bmaf}(bm\ 45\%) = 1.03 \text{ GI} + 10.2 \quad (\text{Eq.1})$$

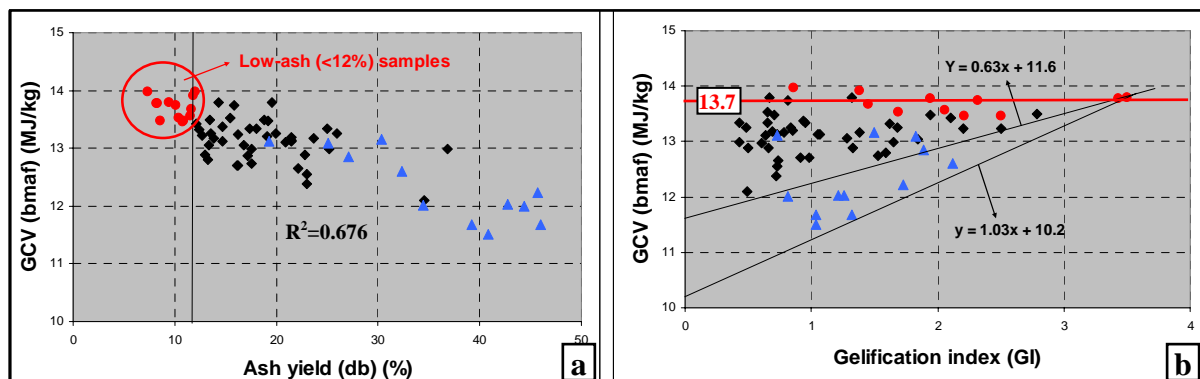
$$\text{and } y = 0.63 x + 11.6 \text{ which corresponds to: } GCV_{bmaf}(bm\ 45\%) = 0.63 \text{ GI} + 11.6 \quad (\text{Eq.2})$$

Considering the upper limit of the GCV $_{bmaf}$  at nearly 14 MJ/kg (**Fig. 7.8-b**), for the entire set of data comprising all the three “petrographic” units (**Tab. 7.1**), the entire field of GCV $_{bmaf}$  versus GI values above the **Eq. 1** line may be described by the following expression:

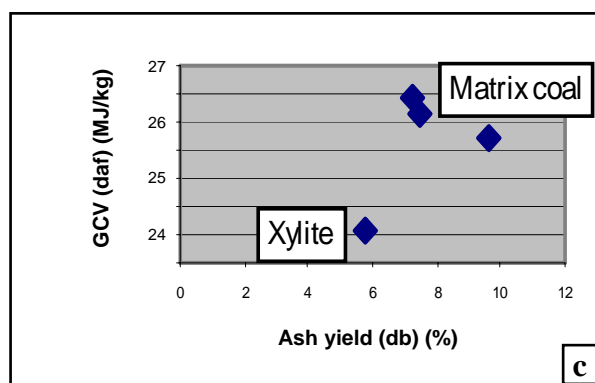
$$14 \text{ MJ/kg} > GCV_{bmaf}(bm\ 45\%) > (1.03 \text{ GI} + 10.2 \text{ MJ/kg}) \quad (\text{Expr. 1})$$



**Fig. 7.7:** Variations of the ash yield at the dry basis (a), gross calorific value at the bed-moist, ash-free basis (GCVbmaf) (b), and of the gelification index (c) throughout the P-9k/92 lignite seam profile. The GCVbmaf variation is presented by three curves: considering the 50 % (the left-most curve), the 45 % (the central curve in bold) and the 40 % (the right-most curve) bed moisture contents. Filled circle dots are low-ash (<12% ash yield) samples with notably the highest GCVbmaf values with an average of 13.7 MJ/kg at 45 % BM content. Open circles are high GCVbmaf samples with 12 to 20 % ash yield.



**Fig. 7.8:** a) and b) Dependence of the GCVbmaf (at 45 % bm) on the ash yield, and the relation between the GCVbmaf (at 45 % bm) and the gelification degree – based on data from the P-9k/92 lignite seam profile (Tab. 7.1). Samples from “petrographic” unit I (which is mineral-rich) are marked by triangles, samples from units II and III are marked by diamonds and circles together, and the circles only are mineral-poor (low-ash, i.e. <12 % ash yield) samples. c) Difference in GCVdaf between low-ash xylite and fine-detrital (matrix) lignite – based on data from Tab. 6.5. For the matrix lignite, note also a remarkable negative correlation between the GCV and the ash yield.



Similarly, the field between 14 MJ/kg and above the **Eq. 2** line may be defined by the expression:

$$14 \text{ MJ/kg} > \text{GCVbmaf}_{(bm \ 45\%)} > (0.63 \text{ GI} + 11.6 \text{ MJ/kg}) \quad (\text{Expr. 2})$$

The field between the two lines is therefore defined by:

$$(0.63 \text{ GI} + 11.6 \text{ MJ/kg}) > \text{GCVbmaf}_{(bm \ 45\%)} > (1.03 \text{ GI} + 10.2 \text{ MJ/kg}) \quad (\text{Expr. 3})$$

The GCVbmaf versus GI field between the two lines (**Expr. 3**) includes only lignite samples from the lower-most mineral-rich unit I (triangle signs), whereas the field above the “upper” line (or the **Eq. 2** line) comprises samples from units II and III (and only few samples from unit I). Samples marked by circles are the low-ash (< 12 %), high GCVbmaf, and hence coal rank representative samples.

**Fig. 7.8-b** clearly indicates that the GCVbmaf variability of lignite decreases by increasing gelification character of lignite. In the case of low gelified lignite (GI from 0.5 to ca. 1.5), the GCVbmaf is very variable, ranging from the lowest values of about 12 MJ/kg (or even less in the case of unit I), to the highest (rank representative) values of around 13.7 MJ/kg (average of filled dots in **Fig. 7.8-b**). With increasing gelification, beyond GI of ca 1.5, GCVbmaf approaches more and more to the value of 13.7 MJ/kg. It can be concluded that in heterogeneous coals, characterized by relatively high contents of textinite, attrinite, fusinite and inertodetrinite versus more gelified macerals (see more explanation for GI in the expression below **Tab. 6.15**) the GCVbmaf varies considerably due to both the heterogeneity of organic components and variable mineral matter contents. Heterogeneous peats and lignites mostly form in more fluvially influenced environments, such as forest and bush swamps along shorelines, and, superpositionally speaking, mostly at the bottom of the intermountain lignite/coal seams. As seen from **Fig. 7.8-b**, the variability of the GCV decreases and finally unifies at the highest (rank representative) level when the lignite attains its homogeneous appearance, characterized by a high gelification index and low mineral matter content. Such peats/lignites typically form in the water-stagnant environments of wet forest and/or bush swamps and/or fens with very little riverine inflow as interpreted also for the upper part of the Velenje lignite seam (**Figs. 6.61 and 6.62**).

The next interesting aspect of data in **Fig. 7.8-b** is the field of data for unit I (triangle signs). These data show that the gelification was relatively enhanced in the lowermost ash-rich unit I of the seam. This effect of increased gelification in unit I is more clearly shown in **Fig. 6.63** and was already discussed in **Chap. 6.4.1.4.5**.

## 8. INORGANIC-GEOCHEMICAL CHARACTERIZATION OF THE VELENJE LIGNITE

### 8.1. Samples, methods, analytical results, and accuracy of analytics

Inorganic geochemical characterization of the Velenje lignite was carried out along the lignite-core profile of borehole P-9k/92 (**Figs. 6.22, 6.45, 6.46**). 30 lignite samples, 6 samples from the floor and 3 samples from the roof rocks were analyzed. Minor-element geochemical composition was determined on the basis of the following eleven elements<sup>37</sup>. Si, Al, Fe, Mg, Ca, Na, K, Ti, P, Mn and Cr, expressed as oxides. Trace-element composition was evaluated by the analysis of contents of 46 trace-elements.  $S_{\text{tot}}$ ,  $C_{\text{tot}}$ ,  $C_{\text{org}}$  and loss on ignition (LOI) at 1000 °C were analyzed in addition. The chosen interval samples – i.e, 0.6–2.3 m long, lithotype representative, homogenized and reduced prior to having been analyzed – were the same as for micro-petrographic analysis, but the number of samples was lower (**Tab. 8.1**).

Geochemical analysis was carried out on “whole coal”<sup>38</sup> samples, because the goal was to determine the geochemical composition of intact material. The Acme Analytical Laboratories Ltd. (Vancouver – British Columbia, Canada) was chosen as the analytical laboratory. As recommended by this laboratory, analytical samples from the whole coal samples were prepared with drying, milling, homogenization, and pulverization below 0.1 mm (150 mesh). The weight of the analytical samples was ca. 8 grams. Eleven minor elements were analyzed by the inductively coupled plasma / atomic emission spectrometry (ICP/AES), and 46 trace elements were analyzed by the inductively coupled plasma / mass spectrometry (ICP/MS).  $S_{\text{tot}}$ ,  $C_{\text{tot}}$ ,  $C_{\text{org}}$  were analyzed by Leco. Original analytical data are presented in **Tab. 8.1** (oxides of minor elements), and in **Tabs. 8.2 and 8.3** (trace elements).

The aim of the geochemical characterization was to evaluate the proportions of separate oxides in the inorganic matter and their variability throughout the coal seam, to investigate the dependence between the minor-element composition and the inorganic matter content and to clarify the modes of occurrence of separate elements.

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<sup>37</sup> The eleven cited elements which are typically the main in inorganic matter (or ash forming) are considered the minor elements of coals in the sense of DIESSEL (1992, p.228, 229, 232).

<sup>38</sup> “Whole coal” analysis: the expression is analogous to the well known “whole rock” analysis



**Tab. 8.1:** Contents of minor element oxides, Ba, Ni, and Sc, portions of loss on ignition (LOI) at 1000 °C, contents of total and organic carbon (C<sub>tot</sub>, C<sub>org</sub>), and contents of total sulphur (S<sub>tot</sub>) in pulverised "whole rock / lignite" ("CK") samples. SUM refers to the sum of minor element oxides, Ba, Ni and Sc, and LOI. Samples were analysed in the Acme Anal. Lab. (Vancouver, Canada) by packages "Whole Rock Analysis" (ICP-ES - Group 4A) and »Carbon and Sulphur by Leco Analysis« (Group 2A) (Schedule: ACME in 2005).

EL	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	Cr <sub>2</sub> O <sub>3</sub>	Ba	Ni	Sc	LOI	C <sub>tot</sub>	S <sub>tot</sub>	C <sub>org</sub>	SUM
wt/smp	%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	%	%	%	%	%
103 CK	51.60	17.68	7.24	1.78	1.22	0.50	2.28	0.74	0.17	0.20	0.016	307	32	18	16.4	3.90	0.30	3.16	99.86
100 CK	51.51	17.28	5.82	1.75	1.31	0.49	2.29	0.72	0.16	0.13	0.014	298	37	18	18.3	5.16	0.32	4.68	99.82
97 CK	34.95	12.15	7.26	1.41	0.83	0.24	1.62	0.49	0.09	0.03	0.014	180	29	12	41.3	15.84	4.82	15.77	100.41
95 CK	6.28	3.60	2.07	0.80	1.03	0.07	0.38	0.10	0.17	0.01	0.002	133	<20	3	85.3	46.22	2.23	46.10	99.83
92 CK	1.08	0.78	0.80	0.65	1.45	0.08	0.07	0.02	<0.01	0.01	<0.001	46	<20	1	94.6	54.25	1.81	53.84	99.55
91 CK	2.87	1.84	1.45	0.65	1.34	0.07	0.17	0.06	0.05	0.01	0.004	62	<20	2	91.3	50.53	2.05	50.24	99.82
90 CK	0.91	0.69	0.91	0.49	1.43	0.06	0.05	0.02	<0.01	0.01	<0.001	33	<20	<1	94.6	54.94	1.93	54.55	99.18
84 CK	0.21	0.11	4.52	1.16	48.78	0.02	<0.02	<0.01	0.04	0.86	0.002	81	<20	<1	44.2	13.39	0.13	2.40	99.92
82 CK	3.35	2.14	1.81	0.36	1.54	0.06	0.24	0.06	0.03	0.01	0.004	52	<20	2	90.0	47.20	2.74	47.14	99.60
79 CK	8.10	4.71	2.73	0.47	1.60	0.15	0.47	0.14	0.13	0.01	0.005	140	<20	5	81.0	41.76	2.97	41.68	99.54
74 CK	7.69	4.74	2.79	0.44	1.53	0.12	0.47	0.13	0.20	0.01	0.006	174	<20	5	82.1	43.02	2.86	42.95	100.25
73 CK	1.09	0.84	0.94	0.20	1.40	0.09	0.06	0.03	<0.01	0.01	<0.001	24	<20	2	93.4	53.01	2.13	52.95	98.06
72 CK	1.16	0.91	1.07	0.24	1.91	0.13	0.07	0.03	<0.01	0.01	<0.001	33	<20	2	92.8	53.40	2.33	53.36	98.33
70 CK	5.07	3.23	1.94	0.32	1.50	0.09	0.29	0.10	0.08	0.01	0.003	90	<20	2	87.3	46.51	2.14	46.46	99.94
68 CK	1.67	1.25	0.73	0.21	1.67	0.14	0.08	0.04	0.02	0.01	<0.001	25	<20	1	93.1	51.36	1.70	51.33	98.93
67 CK	4.16	2.69	2.89	0.30	1.56	0.14	0.21	0.09	0.05	0.01	0.001	49	<20	4	87.8	45.93	3.25	45.87	99.91
63 CK	8.70	5.05	2.18	0.40	1.47	0.14	0.44	0.17	0.09	0.01	0.002	105	<20	4	80.9	42.73	2.21	42.67	99.57
60 CK	3.56	2.19	4.18	0.26	1.84	0.13	0.16	0.07	0.02	0.12	0.002	63	20	2	87.2	47.58	1.84	47.24	99.74
59 CK	7.87	4.73	1.40	0.42	1.61	0.16	0.43	0.15	0.08	<0.01	<0.001	98	<20	4	83.1	46.51	1.62	46.47	99.96
58 CK	3.68	2.17	5.93	0.30	2.13	0.16	0.18	0.07	<0.01	0.12	0.002	36	24	2	84.4	43.31	2.44	42.97	99.16
57 CK	7.93	4.82	2.96	0.39	1.65	0.15	0.41	0.16	0.05	<0.01	0.005	76	30	5	81.0	42.83	3.04	42.77	99.54
55 CK	10.25	5.33	2.56	0.44	1.65	0.19	0.49	0.19	0.06	<0.01	0.004	89	<20	5	78.6	42.73	2.59	42.69	99.78
51 CK	7.07	4.04	2.72	0.38	1.53	0.18	0.39	0.13	0.02	<0.01	0.006	65	29	4	83.1	45.44	2.92	45.39	99.58
49 CK	14.65	8.16	3.39	0.57	1.28	0.21	0.84	0.26	0.10	<0.01	0.006	130	38	8	70.1	35.55	2.87	35.50	99.58
46 CK	8.49	4.74	2.91	0.40	1.25	0.21	0.50	0.15	0.07	0.02	<0.001	92	34	4	81.1	43.99	2.66	43.96	99.86
43 CK	9.89	5.82	1.86	0.49	1.32	0.24	0.65	0.18	0.07	0.01	0.004	99	26	6	78.9	42.44	1.88	42.40	99.44
40 CK	0.02	0.05	49.98	0.67	4.44	0.06	0.02	<0.01	0.11	1.00	0.004	35	20	<1	43.3	18.96	0.18	12.73	99.64
37 CK	1.62	1.11	54.12	0.53	3.69	0.07	0.14	0.03	0.18	1.42	0.007	89	29	1	36.5	13.43	0.19	7.84	99.43
35 CK	12.38	6.82	1.57	0.56	1.07	0.22	0.72	0.22	0.11	<0.01	0.005	127	36	7	76.0	41.37	1.56	41.32	99.69
34 CK	0.10	0.04	53.74	0.71	4.48	0.01	<0.02	<0.01	0.17	1.17	0.030	36	123	<1	78.9	14.99	0.10	8.46	99.37
30 CK	10.59	6.09	2.39	0.54	1.05	0.27	0.65	0.19	0.23	0.01	0.003	208	29	7	77.7	41.95	2.05	41.87	99.74
29 CK	17.33	8.87	4.05	0.71	0.85	0.29	1.05	0.30	0.16	0.01	0.006	230	28	9	66.0	32.74	3.21	32.70	99.65
27 CK	22.38	10.49	2.91	0.77	0.73	0.30	1.32	0.37	0.11	<0.01	0.005	215	46	11	60.3	30.31	2.54	30.28	99.71
25 CK B	50.67	17.13	8.18	2.63	3.30	1.03	2.56	0.94	0.16	0.12	0.008	416	56	17	13.4	3.08	0.19	2.06	100.19
25 CK A	50.25	16.90	7.96	2.59	3.10	1.02	2.51	0.93	0.21	0.11	0.010	409	56	18	13.7	2.94	0.15	1.97	99.35
23 CK	43.59	17.87	2.17	0.94	0.57	0.30	2.10	0.75	0.08	0.01	0.013	267	45	17	31.0	11.98	1.23	11.90	99.42
13 CK	34.63	16.28	1.83	1.05	0.71	0.37	2.16	0.60	0.19	0.01	0.013	402	64	18	41.5	19.84	1.02	19.81	99.40
12 CK	41.60	14.79	7.01	1.09	1.10	0.37	2.00	0.71	0.09	0.07	0.008	253	31	16	30.6	11.30	1.91	11.15	99.47
3 CK	29.80	14.15	2.69	0.95	0.70	0.32	1.77	0.50	0.14	0.02	0.008	321	43	15	48.8	22.46	1.80	22.40	99.89

**Tab. 8.2:** Contents of trace elements in the same samples as in **Tab.8.1** – analysed in the same laboratory as in **Tab.8.1**. – »Whole Rock Analysis« (ICP-MS - Group 4B-REE).

EL	ppm																												
	Co	Cs	Ga	Hf	Nb	Rb	Sr	Ta	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
vz/smp	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
103 CK	17.6	9.6	24.6	3.4	13.3	126.3	2	145.2	1.0	12.2	2.9	146	2.3	101.7	30.1	29.2	63.6	7.06	29.7	5.5	1.24	5.24	.83	4.93	1.03	2.79	.41	2.81	.42
100 CK	15.0	10.3	24.0	3.3	13.9	131.3	2	139.5	1.0	10.9	2.9	154	2.5	101.3	28.6	30.1	62.9	6.80	28.5	5.8	1.22	5.58	.92	4.89	.94	2.78	.42	2.73	.38
97 CK	14.1	7.7	16.3	2.6	10.1	98.3	1	58.7	.6	10.2	3.3	126	1.5	80.7	20.9	21.4	43.7	5.03	20.6	4.0	.88	3.41	.55	3.72	.64	1.99	.29	2.20	.34
95 CK	2.5	2.5	4.7	<.5	2.1	26.4	1	169.6	.2	2.4	7.9	28	.4	15.9	5.8	6.7	12.6	1.65	7.0	1.4	.24	1.15	.19	1.00	.21	.68	.08	.55	.08
92 CK	.6	.4	1.3	<.5	<.5	3.9	<1	16.3	.1	.5	6.4	9	.2	3.2	1.4	1.7	2.9	.37	1.3	.3	<.05	.23	.06	.31	<.05	.15	<.05	.09	.03
91 CK	1.7	1.1	3.1	<.5	1.4	11.0	<1	71.1	<1	1.2	5.1	18	.3	10.1	3.2	3.9	7.0	.84	3.8	.7	.16	.68	.09	.57	.11	.29	.05	.27	.05
90 CK	.9	.2	1.6	<.5	<.5	3.1	<1	14.3	<1	.5	8.3	9	.1	3.1	1.5	1.4	2.3	.35	1.2	.5	.10	.31	.05	.29	.06	.07	<.05	.08	.02
84 CK	.5	<.1	.9	<.5	<.5	1.1	<1	402.6	<1	<.1	.8	<.5	.2	<.5	1.9	1.0	1.9	.33	1.4	.3	.09	.54	.05	.20	.06	<.05	.11	.02	.02
82 CK	2.9	1.6	3.3	<.5	1.3	18.7	<1	50.2	.1	2.2	10.4	22	.5	10.0	4.3	4.7	8.3	1.03	4.1	.9	.16	.71	.13	.61	.12	.32	.08	.48	.07
79 CK	2.4	3.2	6.6	.7	1.8	34.9	<1	204.1	.2	4.4	10.4	36	.8	20.1	7.2	9.3	17.3	2.29	9.3	1.6	.37	1.63	.21	1.25	.24	.67	.11	.72	.10
74 CK	2.8	3.4	6.4	.8	1.8	34.9	<1	243.3	.3	2.8	13.2	36	.8	21.7	6.2	9.2	17.9	2.34	10.9	1.5	.30	1.46	.19	1.01	.23	.61	.07	.60	.11
73 CK	.9	.5	.8	<.5	<.5	4.0	<1	11.0	<.1	.6	9.9	15	.1	4.0	2.3	1.6	2.7	.36	1.4	.4	.10	.58	.07	.23	.09	.27	<.05	.23	.03
72 CK	1.0	.5	1.4	<.5	<.5	4.6	<1	13.7	<.1	1.0	12.5	13	.3	4.2	1.9	2.1	3.7	.49	1.7	.4	.10	.58	.06	.28	.07	.20	<.05	.14	.02
70 CK	2.2	2.0	4.3	.6	1.3	20.0	<1	103.4	.2	2.0	9.6	24	.6	14.1	4.3	5.5	9.2	1.18	5.7	1.1	.18	.73	.09	.70	.15	.42	.06	.49	.05
68 CK	.8	.6	1.4	<.5	<.5	6.3	<1	17.2	.1	.8	8.3	16	.2	5.8	2.5	2.4	4.4	.59	2.5	.5	.12	.50	.07	.36	.07	.23	<.05	.26	.03
67 CK	1.9	1.6	3.8	<.5	.8	14.8	<1	64.9	.1	2.8	10.3	21	.5	12.6	4.7	5.5	9.1	1.15	5.2	.9	.27	.79	.12	.69	.18	.41	<.05	.45	.08
63 CK	3.8	3.5	7.5	.6	3.7	34.3	<1	140.8	.3	3.8	12.6	46	1.4	25.1	10.0	10.9	19.1	2.36	10.3	2.0	.43	1.87	.25	1.61	.30	.84	.14	.79	.13
60 CK	1.5	1.2	3.1	<.5	.9	12.0	2	26.0	<.1	1.6	5.9	21	.3	11.2	5.0	4.7	7.9	1.04	4.1	.9	.17	1.09	.11	.62	.14	.35	.06	.41	.05
59 CK	2.9	3.1	6.1	.7	2.9	28.5	2	102.6	.3	2.7	10.1	36	.8	24.1	6.2	9.6	16.9	2.20	9.6	1.3	.34	1.37	.16	1.08	.23	.67	.09	.57	.07
58 CK	2.2	1.3	3.4	<.5	.6	13.3	1	26.2	<.1	2.5	11.3	18	.6	11.7	5.4	5.0	8.5	1.00	4.3	.9	.22	1.01	.11	.50	.18	.43	.06	.62	.07
57 CK	3.6	3.1	6.7	.8	2.8	29.4	2	82.6	.3	3.9	12.0	38	1.0	22.7	8.5	9.8	16.9	2.02	7.6	1.5	.39	1.83	.25	1.16	.28	.81	.10	.76	.11
55 CK	4.4	3.4	7.8	1.1	3.6	35.2	2	86.7	.3	5.1	12.8	44	.9	28.5	8.9	12.2	20.6	2.65	11.4	1.7	.45	1.87	.25	1.39	.30	.77	.13	.73	.12
51 CK	3.6	2.7	5.3	.5	2.2	25.9	<1	51.1	.1	3.5	9.3	36	.6	20.4	8.3	9.2	15.5	1.86	6.9	1.3	.34	1.35	.22	1.07	.26	.73	.10	.56	.11
49 CK	5.1	5.7	10.5	.9	5.0	54.6	1	115.9	.4	5.4	11.4	57	1.0	38.7	13.1	18.7	32.3	3.83	16.7	2.6	.57	1.98	.33	1.89	.42	1.08	.13	1.14	.15
46 CK	7.0	3.1	6.8	.7	3.3	32.5	<1	62.4	.2	3.2	9.8	45	.8	25.7	10.0	10.6	17.9	2.32	10.9	1.9	.42	2.03	.25	1.43	.29	.85	.12	.73	.15
43 CK	3.9	4.0	8.1	.8	3.3	41.2	<1	77.6	.3	4.6	9.3	44	1.0	29.9	12.0	13.9	23.1	2.87	13.4	2.2	.57	2.09	.34	1.95	.35	1.01	.17	.97	.15
40 CK	.9	<.1	1.3	<.5	<.5	.7	<1	2.2	<.1	.1	<.5	.1	<.5	.1	<.5	.5	.8	.17	.8	.4	.16	.79	.09	.49	.11	.29	.06	.27	.05
37 CK	1.7	.7	3.2	<.5	<.5	8.6	<1	14.6	<.1	1.3	1.3	10	.4	5.8	11.8	2.9	5.2	.70	3.7	1.1	.33	1.77	.27	1.34	.28	.67	.08	.45	.07
35 CK	3.9	4.8	10.5	1.0	5.2	45.9	<1	101.5	.3	5.3	8.5	63	1.3	33.1	14.1	16.5	27.9	3.64	15.5	2.6	.54	2.67	.37	2.08	.42	1.20	.17	1.27	.20
34 CK	1.3	<.1	1.0	<.5	<.5	1	2.2	<.1	.3	<.1	<.5	.1	.8	<.5	6.4	.6	.7	.15	.6	.3	.12	.63	.09	.43	.12	.27	.06	.37	.04
30 CK	4.5	3.8	7.8	.7	3.5	41.4	<1	158.7	.3	4.8	8.4	49	.9	28.2	12.1	13.8	24.0	2.94	12.3	2.1	.55	2.16	.28	1.62	.35	1.06	.15	1.06	.17
29 CK	8.6	6.2	13.7	1.2	6.4	61.8	<1	161.4	.3	7.2	13.9	81	1.3	43.4	18.8	20.2	37.7	4.44	20.3	3.2	.78	3.06	.47	2.87	.54	1.66	.24	1.41	.24
27 CK	10.3	7.4	15.6	2.0	7.8	81.5	<1	14.7	.6	10.3	12.0	97	1.8	55.9	20.9	26.3	47.9	5.77	25.2	3.9	.89	3.78	.59	3.12	.62	1.76	.29	1.82	.30
25 CK B	16.5	8.7	22.0	4.9	17.0	20.1	6	123.8	1.5	14.3	2.9	137	2.5	162.6	32.0	38.6	74.8	8.43	34.8	6.5	1.53	6.03	.89	5.04	.98	3.08	.46	3.17	.47
25 CK A	16.7	9.0	24.1	5.1	18.2	121.0	5	122.0	1.2	14.8	3.1	133	25.4	161.3	32.7	38.8	73.7	8.55	35.6	6.1	1.50	6.19	.96	5.36	1.10	3.03	.41	3.24	.49
23 CK	11.8	12.7	25.3	4.8	15.3	122.3	3	173.4	1.3	13.3	8.6	121	2.9	158.2	37.4	44.2	83.2	9.59	39.7	6.9	1.54	6.52	1.07	5.83	1.13	3.28	.52	3.03	.51
13 CK	20.6	11.1	25.2	2.5	14.6	128.6	2	315.6	.9	13.1	13.3	194	3.0	98.8	36.4	45.1	76.1	9.22	37.1	6.5	1.48	5.74	.88	5.01	1.06	3.01	.42	3.14	.46
12 CK	11.6	10.3	21.4	4.4	14.6	104.1	2	109.1	1.0	10.4	4.8	119	2.4	162.1	37.1	36.7	70.7	8.00	32.9	5.9	1.52	5.96	1.00	6.02	1.11	3.68	.51	3.47	.52
3 CK	12.8	9.7	19.1	2.4	9.8	98.3	2	227.0	.7	11.2	12.2	126	1.9	75.6	26.8	33.5	58.7	7.10	28.3	5.0	1.08	4.10	.73	3.93	.77	2.23	.34	2.44	.38

**Tab. 8.3:** Contents of trace elements in the same samples as in **Tab.8.1** – analyzed in the same laboratory as in **Tab.8.1** – »Whole Rock Analysis« (ICP-MS - Group 1DX).

vz/smp	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ni ppm	As ppm	Cd ppm	Sb ppm	Bi ppm	Ag ppm	Au ppb	Hg ppm	Tl ppm	Se ppm
103 CK	1.1	28.2	22.9	101	37.8	5.1	.3	.2	.3	.1	< .5	.13	.4	.9
100 CK	1.0	26.2	23.2	93	40.0	5.2	.4	.2	.3	.1	< .5	.12	.3	1.0
97 CK	3.9	20.8	16.5	69	32.1	8.0	.3	.3	.3	.1	< .5	.12	.5	2.3
95 CK	8.9	8.1	8.2	20	8.5	4.7	.2	.3	.2	< .1	1.5	.09	.1	.5
92 CK	7.8	3.3	1.7	9	2.6	2.5	.1	.2	.2	< .1	< .5	.05	< .1	< .5
91 CK	7.1	6.3	4.3	6	5.4	3.8	< .1	.3	.3	< .1	.9	.06	.1	< .5
90 CK	7.8	3.3	1.9	16	3.7	2.9	< .1	.2	.4	< .1	< .5	.06	< .1	< .5
84 CK	1.6	.5	.4	57	1.4	.9	< .1	< .1	< .1	< .1	< .5	.02	< .1	< .5
82 CK	12.7	7.0	6.2	12	5.6	5.0	.2	.4	1.0	< .1	.6	.07	.1	.7
79 CK	10.3	11.1	8.3	9	8.3	6.9	.1	.4	.2	< .1	2.1	.08	.1	.8
74 CK	18.9	11.9	8.4	16	8.4	7.3	.1	.6	.2	< .1	2.3	.09	.1	1.2
73 CK	14.0	3.7	2.2	15	2.9	5.1	< .1	.3	.1	< .1	.7	.04	< .1	< .5
72 CK	11.9	4.9	2.6	17	3.7	5.0	.1	.3	.1	< .1	2.2	.06	.1	< .5
70 CK	8.1	6.9	8.5	8	5.4	7.1	< .1	.2	.2	< .1	1.9	.07	.1	.6
68 CK	8.5	4.4	3.6	18	3.4	5.6	.1	.2	.1	< .1	.9	.05	.1	< .5
67 CK	12.8	7.0	8.2	12	7.3	8.6	< .1	.4	.2	< .1	.5	.07	.1	.7
63 CK	8.8	11.4	16.4	5	9.5	11.9	.1	.4	.2	< .1	1.7	.08	.1	1.1
60 CK	5.9	5.9	5.8	62	6.8	6.9	.3	.2	.1	< .1	.8	.06	.1	.9
59 CK	6.4	11.0	13.4	8	6.6	8.7	.2	.3	.2	< .1	.7	.10	.1	.7
58 CK	9.5	6.5	5.8	37	8.7	8.2	.2	.3	.1	< .1	.6	.07	.1	1.2
57 CK	13.6	14.6	13.9	13	13.5	12.1	.2	.6	.2	.1	1.5	.11	.2	1.4
55 CK	9.6	11.4	13.0	27	11.4	10.0	.2	.4	.3	.1	1.7	.16	.1	1.3
51 CK	10.2	9.4	8.3	24	10.6	10.9	.2	.3	.2	< .1	1.0	.09	.1	1.4
49 CK	14.5	18.7	23.6	32	27.0	17.9	.7	.7	.4	.1	1.9	.17	.2	1.9
46 CK	14.3	13.1	20.4	35	22.5	23.2	.3	.4	.2	< .1	2.8	.13	.1	1.9
43 CK	9.6	16.9	15.0	43	15.2	13.6	.2	.6	.3	.1	2.0	.13	.1	1.2
40 CK	2.5	.7	1.2	466	17.0	1.2	.9	< .1	< .1	< .1	< .5	.14	< .1	< .5
37 CK	5.0	4.6	5.1	273	18.0	3.7	.8	.1	.1	< .1	< .5	.05	< .1	< .5
35 CK	5.0	15.9	11.7	46	14.3	13.1	.8	.3	.4	< .1	1.9	.12	.1	1.1
34 CK	5.7	4.8	1.1	410	118.1	1.3	.4	< .1	.1	< .1	< .5	.10	< .1	< .5
30 CK	8.2	15.2	12.2	46	16.0	15.0	.3	.4	.3	< .1	< .5	.12	.1	1.3
29 CK	11.2	23.5	23.1	54	27.6	23.9	.7	.8	.4	.1	< .5	.21	.1	2.7
27 CK	6.3	23.1	17.8	110	24.8	18.2	.6	.7	.5	.1	1.0	.17	.2	2.4
25 CK B	1.1	29.4	19.4	108	45.6	7.2	.3	.3	.4	.1	.8	.20	.2	< .5
25 CK A	.9	28.1	19.6	104	49.2	7.5	.3	.3	.4	.1	1.6	.18	.2	< .5
23 CK	4.7	25.1	38.0	264	32.1	13.1	1.0	.7	.6	.1	1.1	.22	.5	1.5
13 CK	10.2	41.0	33.3	51	45.2	20.9	.9	1.8	.6	.1	.8	.27	.2	2.7
12 CK	2.5	26.2	29.6	150	28.2	16.6	1.1	.6	.4	.1	1.4	.20	.6	3.0
3 CK	8.5	28.4	28.0	117	33.8	28.0	.8	.8	1.2	.1	1.0	.24	.2	2.9

he accuracy of results was tested by analyzing standard CRM 180 material (European Commission – Joint Research Centre – IRMM – Geel, Belgium), and by three reruns of five randomly chosen samples (**Tab. 8.4** and **8.5**). The well known NBS coal and coal ash standards were not used because they were not available to purchase at the time of the study. As seen from **Tab. 8.4**, only a limited number of elements could be tested due to a relatively low number of coinciding certified and analyzed elements. Among the tested elements (Ba, Zn, V, Ni, La, Cu, Pb, As, Th and Cd), very high accuracy exists for Ba and Th, and a reliable one for Zn, V, Ni, La and Cu. Low accuracy was found for Pb, and very low for As and Cd. For As and Cd, analyzed values were 2 times greater than the reference values!

**Tab. 8.4:** Analyzed (A) and reference (R) values for the CRM 180 standard material (in ppm). Analyzed values are from lignite in the JV-768 well (sample 58; GeoZS archive C-II-30d/a<sub>3</sub>-156/5-112).

	Ba	Zn	V	Ni	La	Cu	Pb	As	Th	Cd
<b>A</b>	146,5	19,0	14,0	13,5	5,0	7,0	10,0	9,0	2,0	0,4
<b>R</b>	157	27,4	19,3	16	6,5	9,1	17,5	4,23	2,2	0,212
<b>A/R (%)</b>	93	69	73	<84	77	77	57	213	91	<189

**Tab. 8.5:** Three reruns of four lignite samples (in bold), four reruns of one marl sample (in italics) and reruns of the laboratory itself. Stdev – standard deviation; CV – coefficient of variation. Values for groups of samples that comprise one or more values under the detection limit are not cited.

Element	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	Cr <sub>2</sub> O <sub>3</sub>	Ba	Ni	Sc	LOI	TOT/C	TOT/S	ORG/C	SUM
Vz./Smpl.	%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	%	%	%	%	%
<b>104 CK</b>	1,22	0,79	0,70	0,31	1,87	0,07	0,08	0,03	0,04	0,03		21		1	93,90	52,29	3,52	52,16	99,04
<b>111 CK</b>	1,79	0,99	0,85	0,35	1,98	0,07	0,12	0,03	0,05	0,03		19		1	93,20	51,31	3,57	51,19	99,47
<b>119 CK</b>	1,45	0,93	0,76	0,33	1,83	0,06	0,10	0,03	0,02	0,03		16		2	93,90	51,51	3,61	51,44	99,45
stdev	0,29	0,10	0,08	0,02	0,08	0,01	0,02	0,00	0,02	0,00		3		1	0,40	0,52	0,05	0,50	
KV / CV	19	11	10	6	4	9	20	0	42	0		13		43	0	1	1	1	
<b>105 CK</b>	1,83	1,24	0,90	0,36	2,13	0,07	0,11	0,06	0,03	0,03		25		2	92,40	50,14	3,21	50,01	99,17
<b>112 CK</b>	2,05	1,31	0,92	0,37	2,05	0,10	0,14	0,06	0,03	0,03		33		1	93,00	50,63	3,20	50,52	100,06
<b>120 CK</b>	2,03	1,29	0,96	0,38	2,29	0,06	0,11	0,06	0,02	0,03		26		2	92,80	49,94	3,16	49,86	100,04
stdev	0,12	0,04	0,03	0,01	0,12	0,02	0,02	0,00	0,01	0,00		4		1	0,31	0,36	0,03	0,35	
KV / CV	6	3	3	3	6	27	14	0	22	0		16		35	0	1	1	1	
<b>106 CK</b>	0,22	0,36	0,40	0,36	2,42	0,07		0,01	0,03	0,07		124		1	94,20	52,39	3,36	52,33	98,16
<b>114 CK</b>	0,46	0,38	0,44	0,38	2,49	0,05		0,01	0,03	0,08		79		1	94,50	52,10	3,39	51,99	98,88
<b>122 CK</b>	0,43	0,38	0,43	0,39	2,56	0,09		0,01	0,02	0,07		70		1	93,80	52,19	3,37	52,12	98,23
stdev	0,13	0,01	0,02	0,02	0,07	0,02		0,00	0,01	0,01		29		0	0,35	0,15	0,02	0,17	
KV / CV	35	3	5	4	3	29		0	22	8		32		0	0	0	0	0	
<b>107 CK</b>	2,25	1,66	0,47	0,41	2,54	0,08	0,08	0,06	0,02	0,03		26		3	91,50	51,31	2,22	51,04	99,10
<b>115 CK</b>	2,14	1,56	0,46	0,39	2,48	0,06	0,08	0,06	0,03	0,03		23		3	91,90	51,80	2,28	51,55	99,19
<b>123 CK</b>	2,37	1,68	0,49	0,42	2,67	0,09	0,09	0,06	0,01	0,03		29		3	91,30	51,31	2,27	51,14	99,22
stdev	0,12	0,06	0,02	0,02	0,10	0,02	0,01	0,00	0,01	0,00		3		0	0,31	0,28	0,03	0,27	
KV / CV	5	4	3	4	4	20	7	0	50	0		12		0	0	1	1	1	
<b>KV poprec</b>	<b>16</b>	<b>5</b>	<b>5</b>	<b>4</b>	<b>4</b>	<b>21</b>	<b>10</b>	<b>0</b>	<b>34</b>	<b>2</b>	<b>0</b>	<b>18</b>	<b>0</b>	<b>19</b>	<b>0</b>	<b>1</b>	<b>1</b>	<b>1</b>	
<b>CV average</b>																			
<i>110 CK</i>	0,15	0,09	4,65	1,20	49,77			0,05	0,88			84			43,10	13,48	0,13	2,00	99,92
<i>RE 110 CK</i>	0,19	0,11	4,60	1,20	49,53			0,05	0,88			93			43,00	13,39	0,14	2,05	99,64
<i>118 CK</i>		0,03	4,64	1,19	49,74			0,06	0,88			86			43,20	13,39	0,14	2,09	99,77
<i>125 CK</i>	0,16	0,07	4,68	1,20	49,32			0,05	0,88			92			43,30	13,48	0,16	2,19	99,72
stdev	0,02	0,03	0,03	0,01	0,21			0,01	0,00			4			0,13	0,05	0,01	0,08	
KV / CV	17	34	1	0	0			7	0			4			0	0	7	3	
STAND SO-17/CSB	61,34	13,77	5,81	2,35	4,67	4,09	1,40	0,60	1,02	0,54	0,44	400	31,00	23	3,40	2,40	5,29	0,51	99,48
STAND SO-17/CSB	61,06	13,71	5,82	2,38	4,64	4,02	1,42	0,59	1,00	0,53	0,44	402	40,00	23	3,40	2,42	5,20	0,54	99,06
RE 49 CK	14,85	8,31	3,44	0,58	1,32	0,20	0,81	0,26	0,08	0,01	0,00	132	47,00	8	70,20	35,55	2,88	35,50	100,07
49 CK	14,65	8,16	3,39	0,57	1,28	0,21	0,84	0,26	0,10	0,01	0,01	130	38,00	8	70,10	35,55	2,87	35,50	99,58

Table 8.5 - continuation

Element	Co	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Vz./Samp	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
104 CK	1,1	0,80	1,5	0,7	5,9	39,2	0,6	3,7	9	0,2	4,3	2,5	1,9	3,5	0,49	1,9	0,5	0,09	0,35	0,06	0,31	0,08	0,21	0,25	0,03	0,25	0,03	0,25	0,03
111 CK	1,1	0,80	2	0,7	6,6	50,1	0,6	4,6	11	0,2	6,2	2,6	2,1	4,1	0,55	2,5	0,5	0,12	0,53	0,07	0,34	0,1	0,26	0,23	0,04	0,23	0,04	0,23	0,04
119 CK	0,8	0,80	1,3	0,6	6,3	50,5	1,1	4,6	8	0,2	6	2,8	2	3,9	0,55	2,2	0,4	0,13	0,43	0,08	0,3	0,11	0,25	0,21	0,04	0,21	0,04	0,21	0,04
stdev	0,17	0,00	0,36	0,06	0,35	6,41	0,29	0,52	1,53	0,00	1,04	0,15	0,10	0,31	0,03	0,30	0,06	0,02	0,09	0,01	0,02	0,03	0,02	0,03	0,02	0,01	0,02	0,01	0,01
KV/CV	17	0	23	9	6	14	38	12	16	0	19	6	5	8	7	14	12	18	21	14	7	16	11	9	16	9	16	9	16
105 CK	1,3	0,9	2	0,8	7,4	47,2	0,7	5	11	0,3	6,4	2,1	2,4	4,6	0,56	2,3	0,4	0,08	0,28	0,06	0,38	0,09	0,18	0,16	0,02	0,16	0,02	0,16	0,02
112 CK	1,2	0,9	1,7	1,1	8,7	52,3	1	4,9	12	0,3	7,7	2	2,6	4,7	0,6	2,3	0,6	0,09	0,35	0,07	0,44	0,08	0,2	0,15	0,03	0,15	0,03	0,15	0,03
120 CK	1,7	0,7	1,9	1,1	7,1	51,9	0,7	5,1	11	0,1	6,2	2,2	2,4	4,6	0,52	2,1	0,3	0,13	0,43	0,06	0,42	0,09	0,22	0,17	0,03	0,17	0,03	0,17	0,03
stdev	0,26	0,12	0,15	0,17	0,85	2,84	0,17	0,10	0,58	0,12	0,81	0,10	0,12	0,06	0,04	0,12	0,15	0,03	0,08	0,01	0,03	0,01	0,02	0,01	0,01	0,01	0,01	0,01	0,01
KV/CV	19	14	8	17	11	6	22	2	5	49	12	5	5	1	7	5	35	26	21	9	7	10	6	22	6	22	6	22	6
106 CK	0,4	0,4	0,4	1,8	2,9	52,1	4,1	4,1	1,8	1,1	1,1	1,1	1,1	1,8	0,21	1,3	0,2	0,2	0,03	0,2	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
114 CK	0,4	0,4	0,4	2,9	52,5	52,5	4,9	4,9	1,3	1	1,9	0,21	1,1	1,9	0,21	1,1	0,2	0,2	0,01	0,18	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
122 CK	0,2	0,2	0,2	1,2	52,6	52,6	4,8	4,8	3,2	1	0,8	1,6	0,21	0,7	0,2	0,2	0,16	0,03	0,06	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11
stdev	0,12	0,12	0,12	0,86	0,86	0,26	0,44	0,44	0,98	0,06	0,15	0,15	0,15	0,15	0,00	0,31	0,00	0,02	0,01	0,08	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
KV/CV	35	35	35	44	44	1	9	9	47	6	16	9	0	30	0	30	0	12	49	52	10	10	10	10	10	10	10	10	10
107 CK	3,6	0,9	2,9	2,4	4,9	58,3	0,8	4,4	20	0,3	5,2	7,5	2,6	5,2	0,68	3,9	0,9	0,24	1,02	0,17	1,06	0,22	0,68	0,08	0,58	0,08	0,58	0,08	0,58
115 CK	3,9	0,6	2,8	1,5	3,6	59,4	1,3	4,3	19	0,2	4,6	7,7	2,3	5	0,66	3,3	0,8	0,24	1,05	0,16	1,21	0,22	0,58	0,09	0,48	0,09	0,48	0,09	0,48
123 CK	3,5	0,8	2,6	2,1	4,3	61,6	1,7	4,3	22	0,4	6,2	8,1	2,3	5,3	0,67	3,7	0,8	0,24	1,31	0,19	0,98	0,22	0,59	0,09	0,59	0,09	0,59	0,09	0,59
stdev	0,21	0,15	0,15	0,46	0,65	1,68	0,45	0,06	1,53	0,10	0,81	0,31	0,17	0,15	0,01	0,31	0,06	0,00	0,16	0,02	0,12	0,00	0,06	0,01	0,06	0,01	0,06	0,01	0,06
KV/CV	6	20	6	23	15	3	36	1	8	33	15	4	7	3	1	8	7	0	14	9	11	0	9	7	11	14	7	11	14
KV popr. CV	10	17	9	0	12	19	0	6	0	24	6	7	21	23	5	8	5	4	14	14	11	17	20	19	6	10	2	7	13
averag	1	1	1	1,6	1,6	406,8	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,9	1,3	2,5	0,38	1,4	0,3	0,09	0,38	0,05	0,2	<0,05	0,06	0,06	0,06	0,06	0,06
RE 110 CK	1	1	1	0,9	0,9	403,7	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,8	0,9	1,6	0,25	1,3	0,4	0,08	0,5	0,06	0,16	0,06	0,08	0,08	0,08	0,08	0,08
118 CK	0,6	0,6	0,6	1	1	374	1	1	1	1	1	1	1	1,7	0,8	1,5	0,24	1,4	0,3	0,1	0,45	0,05	0,18	<0,05	0,11	0,11	0,11	0,11	0,11
125 CK	1	1	1	0,9	0,9	393,3	0,8	0,8	0,8	0,8	0,8	0,8	0,8	1,8	1	1,8	0,26	1,4	0,4	0,06	0,46	0,05	0,18	<0,05	0,12	0,12	0,12	0,12	0,12
stdev	0,20	0,20	0,20	0,34	0,34	14,81	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,22	0,45	0,07	0,05	0,06	0,02	0,05	0,01	0,02	0,03	0,03	0,03	0,03	0,03	0,03
KV/CV	22	22	22	31	31	4	9	9	9	9	9	9	9	5	22	24	23	4	16	21	11	10	9	30	30	30	30	30	30
STAND	18,2	3,9	19,5	11,8	25,1	22,8	9	307,6	4,5	11,3	11	130	10,5	363,7	27,4	10,4	23,6	2,98	14,1	3,4	1,10	3,78	0,66	4,18	0,91	2,80	0,44	2,84	0,45
SO-17	18,1	3,9	19,4	12,2	25,6	22,3	11	311,9	4,5	11,8	11,1	130	10,6	361,5	27,6	11,3	23,5	3,01	14,1	3,3	1,01	3,75	0,65	4,14	0,91	2,80	0,42	2,96	0,44
STAND	5,1	5,7	10,5	0,9	5,0	54,6	1	115,9	0,4	5,4	11,4	57	1,0	38,7	13,1	18,7	32,3	3,83	16,7	2,6	0,57	1,98	0,33	1,89	0,42	1,08	0,13	1,14	0,15
49 CK	5,5	5,7	11,3	1,0	6,0	56,2	1	115,5	0,4	6,6	11,7	58	1,1	36,8	12,4	18,3	32,8	3,90	17,5	2,4	0,62	2,26	0,36	1,85	0,44	1,24	0,18	1,24	0,14
RE49CK	5,5	5,7	11,3	1,0	6,0	56,2	1	115,5	0,4	6,6	11,7	58	1,1	36,8	12,4	18,3	32,8	3,90	17,5	2,4	0,62	2,26	0,36	1,85	0,44	1,24	0,18	1,24	0,14



*Table 8.5 - continuation*

Element	Mo	Cu	Pb	Zn	Ni	As	Cd	Sb	Bi	Ag	Au	Hg	Tl	Se
Vz. / Sample	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppm	ppm	ppm
104 CK	6,5	2,7	2,1	9	2,7	4		0,3	0,1			0,05	0,1	6,5
111 CK	7,4	3,4	1,6	11	2,9	4		0,4	0,1			0,05	0,1	
119 CK	7,5	3,6	1,6	12	2,7	4		0,3	0,1			0,06	0,1	
stdev	0,55	0,47	0,29	1,53	0,12	0,00		0,06	0,00			0,01	0,00	
KV / CV	8	15	16	14	4	0		17	0			11	0	
105 CK	14	5,4	2,2	11	3	5,6	0,1	0,6			0,9	0,04	0,2	
112 CK	13,6	4,6	2,4	12	3	5,5	0,1	0,6			1	0,05	0,2	
120 CK	12,7	5,2	2,2	11	3	6	0,1	0,7			2,3	0,05	0,2	
stdev	0,67	0,42	0,12	0,58	0,00	0,26	0,00	0,06			0,78	0,01	0,00	
KV / CV	5	8	5	5	0	5	0	9			56	12	0	
106 CK	11	2,4	0,5	8	1,4	6,1		0,5				0,03	0,2	
114 CK	10,8	2,3	0,5	8	1,2	5,8		0,4				0,02	0,2	
122 CK	10,2	2,3	0,5	8	1,4	6		0,4				0,03	0,2	
stdev	0,42	0,06	0,00	0,00	0,12	0,15		0,06				0,01	0,00	
KV / CV	4	2	0	0	9	3		13				22	0	
107 CK	5,3	4,1	1,7	8	1,6	3,6		0,2			0,6	0,04	< ,1	
115 CK	4,8	3,5	1,5	6	1,3	3,5		0,2			0,6	0,03		
123 CK	5,1	4,2	1,6	5	1,6	3,4		0,1			1,1	0,03		
stdev	0,25	0,38	0,10	1,53	0,17	0,10		0,06			0,29	0,01		
KV / CV	5	10	6	24	12	3		35			38	17		
<b>KV popr. CV averag</b>	<b>5</b>	<b>9</b>	<b>7</b>	<b>11</b>	<b>6</b>	<b>3</b>	<b>0</b>	<b>19</b>	<b>0</b>	<b>0</b>	<b>23</b>	<b>16</b>	<b>0</b>	<b>0</b>
110 CK	1,8	0,5	0,3	64	< ,1	1,5	0,1							0,6
RE 110 CK	1,5	0,5	0,4	58	0,2	1,2	0,1							0,6
118 CK	1,7	0,6	0,4	65	< ,1	1,3	0,1							0,5
125 CK	1,6	0,7	0,4	66	< ,1	1,6	0,1							0,8
stdev	0,13	0,10	0,05	3,59		0,18	0,00							0,13
KV / CV	8	17	13	6		13	0							20
STANDARD DS4	6,8	119,9	30,5	157	35,2	22,8	5,2	4,2	4,9	0,3	26,3	0,29	1,2	1,2
STANDARD DS4	7,8	129,4	29,2	164	33,5	22,8	5,4	4,5	5,0	0,3	25,3	0,29	1,1	1,4
RE 49 CK	13,5	18,9	22,3	33	28,0	17,4	0,6	0,4	0,3	0,1	1,1	0,14	0,2	2,0
49 CK	14,5	18,7	23,6	32	27,0	17,9	0,7	0,7	0,4	0,1	1,9	0,17	0,2	1,9

## 8.2. Short discussion whether to analyze “whole coals” or coal ashes, and relation between the ash yield and mineral matter content

As well known, apart from analysing whole coals, inorganic geochemical characterization of coals can be performed by the analysis of coal ashes. In an overview of analytical methods for inorganic constituents in coals, this dilemma was discussed by HUGGINS (2002). An advantage of analysing coal ashes is that they are “pure” inorganic materials with trace element contents typically above the limits of detection. They also ensure a much easier dissolution needed for instrumental analytical methods such as the widely practiced ICP/AES

and ICP/MS. A disadvantage of coal ashes is the loss of volatile elements such as As, Se, Hg, B, halogens, especially if the ashing is done at high temperature, between 400 and 900 °C. Significant changes occur at these temperatures also in the mineralogy of the original mineral material. A compromise between the analyses of the original mineral matter (not affected by high temperature mineralogical and elemental transformations) and “normal” high-temperature ashes (HTA) is the analysis of low-temperature ashes (LTA) gained by ashing at 200 °C. However, the latter – also named after Gluskoter, who introduced it in 1965 - needs special equipment and is hence not very routinely practiced in the laboratories. From similar reasons, also in Slovenia, LT ashing was not practiced up to the present. Most geochemical analyses of coals in Slovenia were carried out on HT coal ashes (MARKIČ, 2006), only UHAN (1991, 1993, 1994/95) analyzed both, the ashes and the whole coals. One of the reasons why mostly ashes were analysed is the fact that these studies, except for the previously mentioned ones by UHAN, were primarily oriented to environmental, not to coal genetical aspects.

It is widely known that ash yield is an easy to be analyzed measure of mineral matter in coal. These two parameters are related by the following equations:

$$MM = 1.08 A + 0.55 S \text{ (PARR, 1928)}$$

$$MM = 1.13 A + 0.47 S_{\text{pyr}} + 0.5 Cl \text{ (GIVEN \& YARZAB, 1978),}$$

$$MM = 1.13 A + 0.5 S_{\text{pyr}} + 0.8 CO_2 + 2.85 S_{SO_4} - 2.85 S_{\text{ash}} + 0.5 Cl \text{ (KING et al., 1936),}$$

where MM – percentage of mineral matter in coal; A – percentage of ash yield of coal; S,  $S_{\text{pyr}}$ ,  $S_{SO_4}$ ,  $S_{\text{ash}}$ , Cl – percentage of different forms of sulphur and of chlorine;  $CO_2$  – percent of carbonate carbon dioxide yield from coal

From the above equations it is evident that the mass of mineral matter exceeds the mass of ash yield by a factor of about 1.1. The loss of water bound in clay minerals (dehydroxylation of clay minerals), the loss of  $CO_2$  from carbonates, the loss of sulphate and some volatile elements mostly account for this mass difference.

### 8.3. Origin of mineral matter in coal

By origin, mineral matter is basically differentiated into the inherent and the adventitious mineral matter. The former encompasses mineral substances which are absorbed from the substratum by the plants themselves during their growth period. After MCCARTHY et al. (1989 – in DIESSEL, 1992, p.233) it can be assumed that if a coal contains up to 5 % (by mass) of ash, it is entirely derived from the inherent mineral matter. At 10 % of total ash, the ratio between inherent and adventitious ashes is already close to fifty-fifty, and at 100 % total ash (e.g. a stone band without organic matter), this consists entirely of the adventitious ash. Essential elements for healthy plant growth are all so called main elements of coals: C, H, O, N, S; then: P, B, K, Na, Ca, Mg, Fe, Mn; and finally a range of trace elements, such as: Zn, Mo, Cu, Co, V, Cl (cited from DIESSEL, 1992, p.229).

Apart from C, H, and O, which are provided by photosynthesis from air and water, other elements – also many other than just cited – are absorbed from substratum or from dissolved inorganic substances in inflowing waters. The latter percolate through the accumulated biomass and specific elements can precipitate from the solution, either to form mineral (crystalline or non-crystalline) compounds or organic-inorganic complexes. Precipitability in the immobile form of an element depends primarily on its availability in the depositional environment and its solubility in water, and secondly on the presence of other suitable

elements or compounds with which the element can combine a stable, water-insoluble compound (DIESSEL, 1992, p.231). Precipitated (authigenic) elements and minerals, respectively, can be syngenetic or epigenetic, the latter precipitated at a time when much of diagenesis had been completed.

Most often, the major part of mineral matter in coals is adventitious and originates from the detrital sediment inflow into the peat-forming environment. The composition of such mineral matter, either more or less homogeneously dispersed throughout coal or occurring as interbeds, depends on the hinterland geology of the peatland. The amount of detrital adventitious mineral matter, as well as its structural and textural characteristics depend on many factors such as climate and weathering processes, tecto-dynamics and base level changes, and the energy level of transporting agents such as waters and winds. Different carbominerites (with 20 to 60 vol.% of minerals), especially carbargilites are of this origin. Volume % of minerals as e.g. revealed from microscopy is roughly related to mass % of ash yield (at dry basis) by the following approximate relation (as ascertained for Carboniferous and Permian bituminous coals) (DIESSEL, 1992, p.122):

$$\% \text{ Minerals (vol.)} = 0.54 \% \text{ Ash (mass)}$$

Concerning the inorganic input into the Velenje peat, two main sources can be considered, one from the andesite tuff with marly intercalations from the south, and another one from the northern carbonates and the more remote tonalite massive.

In quite numerous peat-forming geological environments volcanic ashes are noteworthy, transported by winds over relatively long distances and falling onto the contemporaneously existing peat-lands. As volcanic soils are well known by their fertility, it can also be inferred for peat-forming vegetation that they periodically enhanced its growth where and when they occurred. In coals, inter-layers of volcanic origin, often in fact transformed to paleosols, are termed “tonsteins”. These are relatively thin, but laterally extensive and thus represent “marker” horizons in coal seams.

In the Velenje Pliocene lignite seam, sediments of volcanic origin do not occur, although Pliocene volcanism is known from nearby areas in SE Austria (e.g. Riegersburg) and NE Slovenia (Grad in the Goričko district). However, tuff interlayers in Slovenian coal seams are well known in Zasavje (Trbovlje). This tuff has been dated as  $25 \pm 1.0$  Mio years (ODIN et al., 1994). Most probably, it originates from the andesitic Smrekovec volcanic event (e.g. KUŠČER, 1967; HAFNER, 2000; HINTERLECHNER & PLENIČAR, 1967; KRALJ, 1996).

Oligocene “Smrekovec” andesites and their tuffs are widespread south of the Pliocene Velenje basin (**Chap. 2**). Thus, rocks with an andesitic composition might influence the composition of the deposited sediments as well as the chemical composition of percolating waters in the Velenje basin. In contrast, carbonate rocks dominate at its northern margin. Therefore, dolostones and limestones greatly control water chemistry in this part of the basin. In an overview on the origin and chemical composition of thermal and thermomineral waters in Slovenia, LAPANJE (2006) verified the result of numerous previous papers that the carbonate  $\text{Ca-Mg-HCO}_3$  (or  $\text{Mg-Ca-HCO}_3$ ) water is the most common type of water in aquifers of Slovenia. A similar conclusion can be drawn for waters in Slovenia in general. LAPANJE (2006) also highlights a  $\text{SO}_4$ -enriched subtype of water with a temperature of almost  $50^\circ\text{C}$ , which occurs at the Lajše locality (NW of the Velenje basin) in limestone. If this water was enriched in  $\text{SO}_4$  already during peat accumulation and subsequent diagenesis, it could be

– at least to some degree – responsible for the pyrite/marcasite syngenetic occurrences in the Velenje lignite. Close to the Lajše locality, pure carbonate type water at 29 °C is used in the Topolšica spa. In somewhat longer distances from the Velenje basin, to the NE, the Dobrna spa uses a similar carbonate type water with a temperature of about 35 °C.

#### 8.4. Mineral matter and inorganic matter in coal

As discussed by WARD (2002) (taking into account definitions of GARY et al. (1972) and Standards of Australia (1995, 2000)), mineral matter refers to “the inorganic matter in coal”, which is “the sum of the minerals and inorganic matter within and associated with coal”. In his summary, WARD (2002, p.136) cites the following three types of inorganic constituents:

- Dissolved salts and other inorganic substances in the pore water of coal;
- Inorganic elements incorporated within the organic compounds of coal macerals; and
- Discrete inorganic particles (crystalline or non-crystalline) representing true mineral components

According to WARD (2002), the first two forms of inorganic matter are best described as “non-mineral inorganics”. If – in our case of geochemical analysis of dry coal samples – dissolved salts and inorganics in the pore water are neglected, only the two remaining modes of occurrence remain for further discussion. Inorganic elements incorporated within the organic compounds of the coal macerals are designated to have an organic affinity for geochemical bonding. Elements forming true mineral components are said to have an inorganic affinity for bonding. A range of elements (both minor and trace) can have, in the same coal, both organic and inorganic affinity. An exhaustive list of elements with different bonding affinities is given in DIESSEL (1992, p.239, table 5.10). Elements with an organic affinity for bonding are in general far less numerous than the elements with inorganic affinity. Regarding the coal rank, organic bonding of elements is usually prominent in the case of low rank coals (WARD, 2002, p.136, 155), therefore the number of organically bound elements is supposed to be generally greater in low-rank than in high-rank coals. In the latter, some elements may be released from inorganic associations during coalification (TAYLOR et al., 1998, p.269). Among the most abundant elements with an organic affinity are Ca, Na, Mg and Fe, but many other elements may be incorporated into the organic matter. For example, YUDOVICH (2003) extensively commented geochemical studies related to coal inclusions in sedimentary rocks throughout Russia, which revealed in many cases Ge enrichments in fossil woods, even to economic contents. This phenomenon was explained by “good preservation of the original lignin structure, which might effectively scavenge Ge from solutions” (YUDOVICH, 2003). In woods, this effect was found to be more intensive than in underlying “true” coal seams, which contain less lignin according to YUDOVICH (2003).

Affinity for bonding of specific elements is studied by washability tests, also termed sink-and float-analysis, which is a standardised method using liquids of different specific densities to separate a unique analytical sample of crushed coal into corresponding density fractions. Elements with organic affinity are relatively enriched in low-density fractions, which are “pure” coals, whereas elements of inorganic affinity are enriched in high-density fractions (e.g. diagrams by Warbrooke & Dolan, 1986 – from DIESSEL, 1992, p.238). Because of chemicals and skilled staff needed for the sink-and-float procedure, the latter is rather costly, and was not realized in the frame of work for this monograph. Instead, the geochemistry of

low and high ash coal samples has been compared. A similar approach was applied by LYONS et al. (1989), who compared the geochemistry of vitrinite concentrates and whole coals.

## 8.5. Results of geochemical analysis

### 8.5.1. Minor-element geochemistry

The first step to acquire a useful data set for the minor-element geochemical interpretation was the recalculation of originally analyzed values for the “whole-coal matter” (“dry” basis) (see **Tab. 8.1**) to values on the “dry inorganic matter” basis (= “dry, organic matter free” – *domf* basis) solely, which are given in **Tab. 8.6**. As inferred from **Tab. 8.1**, the whole dry coal matter of a sample can be regarded as to be composed of the sum of the oxides (from SiO<sub>2</sub> to Cr<sub>2</sub>O<sub>3</sub>) plus Ba, Ni, and Sc and of the components that were lost on ignition. The oxides plus Ba, Ni and Sc are considered to represent the inorganic part of dry coal, whereas loss on ignition (LOI) mostly refers to the organic part of coal. This is supported by an excellent positive correlation between the factor “100 minus LOI” and ash yield (coefficient of correlation ( $R^2$ ): 0.99).

The analysis revealed that four oxides, SiO<sub>2</sub> (20–52 %), Al<sub>2</sub>O<sub>3</sub> (15–29 %), Fe<sub>2</sub>O<sub>3</sub> (6–24 %), and CaO (2–34 %) (**Tab. 8.6**) constitute the bulk composition of the inorganic matter in lignite. Very tight positive correlations exist between SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, and TiO<sub>2</sub> contents, whereas there are negative correlations between the contents of SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>, and between SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> and MnO (**Tab. 8.7**). Contents of the minor element oxides significantly depend on the inorganic matter contents. From the minimal (ca. 5 %) up to the 20–25 % inorganic matter contents, SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> increases from 40 to 80 %, whereas above this barrier it is constant (**Fig. 8.1 – graph 2**). On the contrary, CaO, MgO, and Fe<sub>2</sub>O<sub>3</sub> increase with decreasing inorganic matter content below the mentioned 20–25 % threshold (**Fig. 8.1 – graphs 5–9**). Taking into account low shares of C<sub>inorg.</sub>, it is concluded that Ca, Mg, and possibly also Fe are mostly organically bound. A weak negative correlation between SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> and CaO, and almost no correlation between SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> and MgO support this assumption.

K<sub>2</sub>O correlates positively with SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> and thus indicates the presence of illite (or muscovite or K feldspar). However, low absolute K<sub>2</sub>O contents indicate low contents in K-bearing minerals. Similar is true for other minor elements and potentially inferred minerals (e.g. montmorillonite, chlorite etc). The argillitic component within the lignite is therefore supposed to be predominantly of the kaolinite (and quartz) type. Indeed, the predominance of kaolinite over illite was confirmed by mineralogical investigations (**Chap. 8.5.2**). Depletion in K, Mg, Ca, Na etc. containing clay minerals to the benefit of kaolinite is a well known phenomenon in coal seams in comparison to the adjacent floor and roof sediments (e.g. WARD, 1989), especially expected in relatively acid environments. In the case of Velenje, where the environment was relatively alkaline, chemical leaching is not supposed to be very outstanding, therefore, external (clastic) income of kaolinite is also possible.



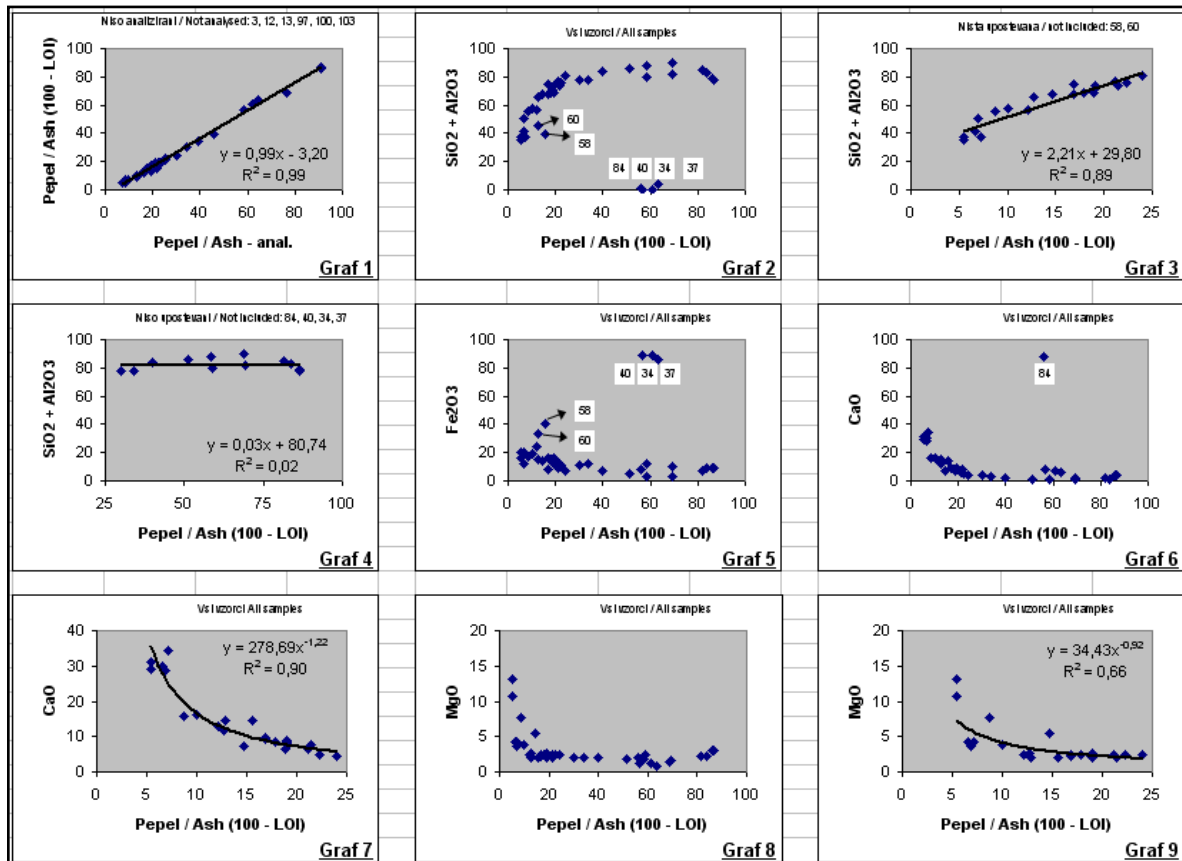
**Tab. 8.6:** Contents of minor element oxides, Ba, Ni and Sc, recalculated on the »dry, organic-matter free« (domf) basis. Ash yields (dry basis) are expressed as analytical values (Ash an.) and as calculated values from 100% - LOI (Ash calc.), respectively. Below is a simplified table with ranges of contents of the most significant minor element oxides

Lithol. unit	Sample N°	Depth (m)	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	MgO (%)	CaO (%)	Na <sub>2</sub> O (%)	K <sub>2</sub> O (%)	TiO <sub>2</sub> (%)	P <sub>2</sub> O <sub>5</sub> (%)	MnO (%)	Cr <sub>2</sub> O <sub>3</sub> (%)	Ba (%)	Ni (%)	Sc (%)	SUM (%)	SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> (%)	LOI (%)	Ash (calc.) (%)	Ash (an.) (%)
ROOF sediments	103 CK	453.85	61.82	21.18	8.67	2.13	1.46	0.60	2.73	0.89	0.20	0.24	0.02	0.037	0.004	0.002	100.00	83.01	16.40	83.60	ni
	100 CK	455.45	63.20	21.20	7.14	2.15	1.61	0.60	2.81	0.88	0.20	0.16	0.02	0.037	0.005	0.002	100.00	84.40	18.30	81.70	analiz
	97 CK	456.70	59.13	20.56	12.28	2.39	1.40	0.41	2.74	0.88	0.15	0.05	0.02	0.030	0.005	0.002	100.00	79.69	41.30	58.70	analiz
	95 CK	458.50	43.23	24.78	14.25	5.51	7.09	0.48	2.62	0.69	1.17	0.07	0.01	0.092	0.014	0.002	100.00	68.01	85.30	14.70	17.21
	92 CK	462.35	21.78	15.73	16.14	13.11	29.25	1.61	1.41	0.40	0.20	0.20	0.02	0.093	0.040	0.002	100.00	37.52	94.60	5.40	8.2
	91 CK	464.25	33.68	21.59	17.01	7.63	15.72	0.82	1.99	0.70	0.59	0.12	0.05	0.073	0.023	0.002	100.00	55.27	91.30	8.70	13.43
	90 CK	465.85	19.84	15.04	19.84	10.68	31.18	1.31	1.09	0.44	0.22	0.22	0.02	0.072	0.044	0.002	100.00	34.89	94.60	5.40	7.38
	84 CK	474.65	0.38	0.20	8.11	2.08	87.51	0.04	0.04	0.02	0.07	1.54	0.00	0.015	0.004	0.000	100.00	0.57	44.20	55.80	
	82 CK	477.55	34.85	22.27	18.83	3.75	16.02	0.62	2.54	0.62	0.31	0.10	0.04	0.054	0.021	0.002	100.00	57.12	90.00	10.00	13.32
	79 CK	482.40	43.71	25.42	14.73	2.54	8.63	0.81	2.54	0.76	0.70	0.05	0.03	0.076	0.011	0.003	100.00	69.13	81.00	19.00	22.98
LIGNITE SEAM	74 CK	490.90	42.38	26.12	15.38	2.42	8.43	0.66	2.59	0.72	1.10	0.06	0.03	0.096	0.011	0.003	100.00	68.50	82.10	17.90	23
	73 CK	492.25	23.31	17.97	20.10	4.28	29.94	1.92	1.28	0.64	0.21	0.21	0.02	0.061	0.043	0.004	100.00	41.28	93.40	6.60	8.28
	72 CK	493.65	20.91	16.41	19.29	4.33	34.44	2.34	1.26	0.54	0.18	0.18	0.02	0.059	0.036	0.004	100.00	37.32	92.80	7.20	9.42
	70 CK	495.65	40.10	25.55	15.34	2.53	11.86	0.71	2.29	0.79	0.63	0.08	0.02	0.071	0.016	0.002	100.00	65.64	87.30	12.70	16.24
	68 CK	498.45	28.67	21.46	12.53	3.60	28.67	2.40	1.37	0.69	0.34	0.17	0.02	0.043	0.034	0.002	100.00	50.12	93.10	6.90	8.57
	67 CK	500.15	34.36	22.22	23.87	2.48	12.88	1.16	1.73	0.74	0.41	0.08	0.01	0.040	0.017	0.003	100.00	56.57	87.80	12.20	16.11
	63 CK	506.70	46.61	27.06	11.68	2.14	7.88	0.75	2.36	0.91	0.48	0.05	0.01	0.056	0.011	0.002	100.00	73.67	80.90	19.10	22.83
	60 CK	511.75	28.39	17.46	33.33	2.07	14.67	1.04	1.28	0.56	0.16	0.96	0.02	0.050	0.016	0.002	100.00	48.85	87.20	12.80	19.15
	59 CK	513.45	46.64	28.03	8.30	2.49	9.54	0.95	2.55	0.89	0.47	0.06	0.01	0.058	0.012	0.002	100.00	74.67	83.10	16.90	19.06
	58 CK	515.40	24.94	14.70	40.18	2.03	14.43	1.08	1.22	0.47	0.07	0.81	0.01	0.024	0.016	0.001	100.00	39.64	84.40	15.60	21.49
FLOOR sediments	57 CK	516.75	42.76	25.99	15.96	2.10	8.90	0.81	2.21	0.86	0.27	0.05	0.03	0.041	0.016	0.003	100.00	68.75	81.00	19.00	22.1
	55 CK	519.20	48.38	25.16	12.08	2.08	7.79	0.90	2.31	0.79	0.28	0.05	0.02	0.042	0.009	0.002	100.00	73.54	78.60	21.40	25.17
	51 CK	526.20	42.89	24.51	16.50	2.31	9.28	1.09	2.37	0.79	0.12	0.06	0.04	0.039	0.018	0.002	100.00	67.39	83.10	16.90	19.92
	49 CK	529.55	49.67	27.67	11.49	1.93	4.34	0.71	2.85	0.88	0.34	0.03	0.02	0.044	0.013	0.003	100.00	77.34	70.10	29.90	34.53
	46 CK	534.50	45.27	25.27	15.52	2.13	6.67	1.12	2.67	0.80	0.37	0.11	0.01	0.049	0.018	0.002	100.00	70.54	81.10	18.90	20.88
	43 CK	538.40	48.13	28.33	9.05	2.38	6.42	1.17	3.16	0.88	0.34	0.05	0.02	0.048	0.013	0.003	100.00	76.46	78.90	21.10	24.97
	40 CK	541.80	0.04	0.09	88.66	1.19	7.88	0.11	0.04	0.02	0.20	1.77	0.01	0.006	0.004	0.000	100.00	0.12	43.30	56.70	58.22
	37 CK	544.20	2.57	1.76	86.00	0.84	5.86	0.11	0.22	0.05	0.29	2.26	0.01	0.014	0.005	0.000	100.00	4.34	36.50	63.50	64.59
	35 CK	546.50	52.23	28.77	6.62	2.36	4.51	0.93	3.04	0.93	0.46	0.04	0.02	0.054	0.015	0.003	100.00	81.01	76.00	24.00	30.3
	34 CK	547.60	0.17	0.07	88.83	1.17	7.41	0.02	0.03	0.02	0.28	1.93	0.05	0.006	0.020	0.000	100.00	0.23	38.90	61.10	61.83
FLOOR sediments	30 CK	552.60	48.05	27.63	10.85	2.45	4.76	1.23	2.95	0.86	1.04	0.05	0.01	0.094	0.013	0.003	100.00	75.69	77.70	22.30	25.08
	29 CK	553.85	51.50	26.36	12.03	2.11	2.53	0.86	3.12	0.89	0.48	0.03	0.02	0.068	0.008	0.003	100.00	77.85	66.00	34.00	39.26
	27 CK	556.40	56.77	26.61	7.38	1.95	1.85	0.76	3.35	0.94	0.28	0.03	0.01	0.055	0.012	0.003	100.00	83.38	60.30	39.70	45.95
	25 CK B	558.00	58.39	19.74	9.43	3.03	3.80	1.19	2.95	1.08	0.18	0.14	0.01	0.048	0.006	0.002	100.00	78.13	13.40	86.60	90.92
	23 CK A	558.00	58.68	19.73	9.29	3.02	3.62	1.19	2.93	1.09	0.25	0.13	0.01	0.048	0.007	0.002	100.00	78.41	13.70	86.30	90.92
FLOOR sediments	23 CK	560.05	63.70	26.12	3.17	1.37	0.83	0.44	3.07	1.10	0.12	0.01	0.02	0.039	0.007	0.002	100.00	89.82	31.00	69.00	76.25
	13 CK	572.80	59.82	28.12	3.16	1.81	1.23	0.64	3.73	1.04	0.33	0.02	0.02	0.069	0.011	0.003	100.00	87.94	41.50	58.50	not
	12 CK	562.50	60.40	21.48	10.18	1.58	1.60	0.54	2.90	1.03	0.13	0.10	0.01	0.037	0.005	0.002	100.00	81.88	30.60	69.40	analiz
	3 CK	568.10	58.33	27.70	5.27	1.86	1.37	0.63	3.46	0.98	0.27	0.04	0.02	0.063	0.008	0.003	100.00	86.03	48.80	51.20	sed

LITHOL. UNIT	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	CaO (%)
Roof sediments	59 - 62	21	7 - 12	1 - 2
Lignite seam	20 - 52	15 - 29	6 - 24	2 - 34
Floor sediments	57 - 64	20 - 28	3 - 10	1 - 4

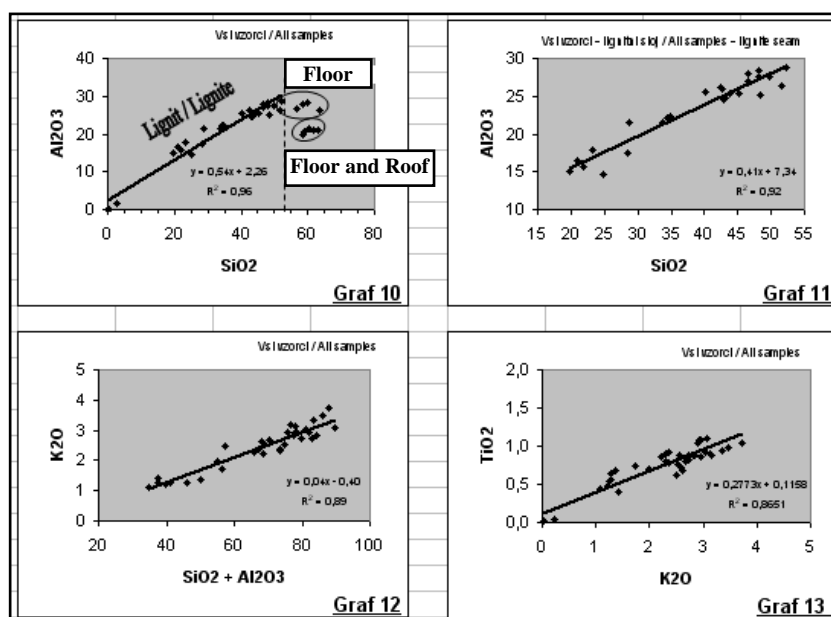
**Tab. 8.7:** Pearson's correlation coefficients ( $r$ ) between the contents of minor element oxides from **Tab. 8.6**; correlations, both positive and negative closer than  $r: |0,6|$  are in bold.

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	Cr <sub>2</sub> O <sub>3</sub>	Ba	Ni	Sc
SiO <sub>2</sub>	1,00	<b>0,83</b>	<b>-0,74</b>	-0,22	<b>-0,62</b>	0,01	<b>0,96</b>	<b>0,96</b>	0,13	<b>-0,78</b>	-0,08	0,32	-0,40	0,57
Al <sub>2</sub> O <sub>3</sub>		1,00	<b>-0,78</b>	-0,05	-0,49	0,26	<b>0,89</b>	<b>0,89</b>	0,39	<b>-0,91</b>	0,03	0,60	-0,06	<b>0,76</b>
Fe <sub>2</sub> O <sub>3</sub>			1,00	-0,15	-0,02	-0,32	<b>-0,75</b>	<b>-0,78</b>	-0,13	<b>0,87</b>	0,13	-0,53	0,00	<b>-0,66</b>
MgO				1,00	0,34	0,42	-0,17	-0,17	0,06	-0,21	0,19	0,52	<b>0,72</b>	0,12
CaO					1,00	0,21	-0,61	-0,56	-0,21	0,30	-0,11	-0,09	0,40	-0,23
Na <sub>2</sub> O						1,00	0,02	0,20	-0,05	-0,43	-0,09	0,35	<b>0,73</b>	0,54
K <sub>2</sub> O							1,00	<b>0,93</b>	0,26	<b>-0,81</b>	-0,02	0,47	-0,33	<b>0,63</b>
TiO <sub>2</sub>								1,00	0,14	-0,86	-0,09	0,39	-0,24	<b>0,68</b>
P <sub>2</sub> O <sub>5</sub>									1,00	-0,27	0,13	<b>0,69</b>	-0,04	0,22
MnO										1,00	-0,05	<b>-0,64</b>	-0,14	<b>-0,81</b>
Cr <sub>2</sub> O <sub>3</sub>											1,00	0,13	0,29	0,06
Ba												1,00	0,33	0,57
Ni													1,00	0,29
Sc														1,00

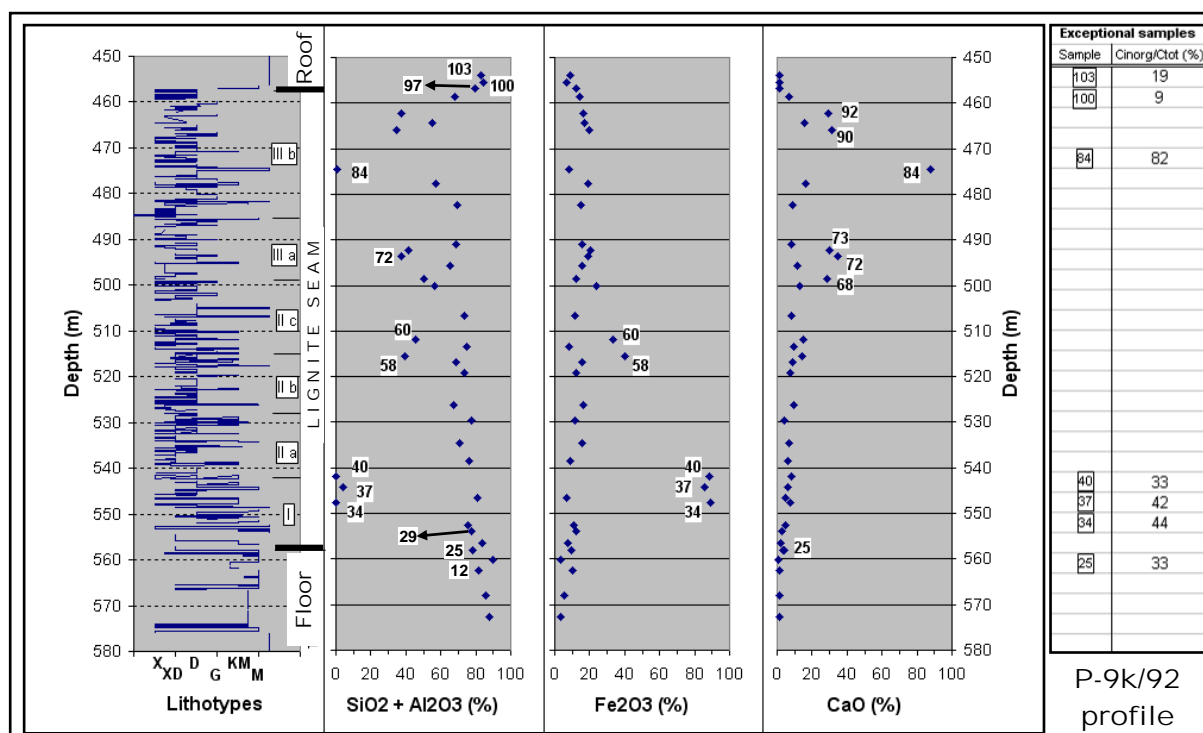


**Fig.8.1:** Correlation graphs: between analyzed high-temperature ash yield and ash yield calculated as 100 % – LOI (graph 1), and between ash yield (as 100 % – LOI) and oxides of minor elements (graphs 2–9). Notable is the geochemical threshold at the 20–25 % ash yield in graphs 2–9. In graphs 6–9, CaO and MgO clearly show increasing contents in the mineral matter of the low-ash lignite samples. Exceptionally Fe-rich samples are designated by numbers (see also **Fig. 8.3**).

Vertical variations of the contents in the four main minor-element oxides throughout the seam in the P-9k/92 profile are presented in **Fig. 8.3**. SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> content decreases upwards – i.e. from the high-ash toward the low-ash lignite. On the contrary, CaO and Fe<sub>2</sub>O<sub>3</sub> slightly



**Fig.8.2:** Correlation graphs between selected oxides of minor elements. In graph 10, depletion in  $Al_2O_3$  versus  $SiO_2$  in the floor and the roof sediments is notable. The correlation between  $SiO_2$  and  $Al_2O_3$  is very tight as shown in graph 11. A positive correlation between  $K_2O$  and  $SiO_2 + Al_2O_3$  in graph 12 implies the presence of illite, but the contents of oxides other than  $CaO$  and  $Fe_2O_3$  are very low indicating a predominantly kaolinitic composition of the argillitic fraction within the coal seam, especially at the bottom.



**Fig. 8.3:** Lithotype log of lignite in borehole P-9k/92 (left) and contents of most significant minor-element oxides in inorganic matter of whole rock / whole lignite samples (CK samples from Tab. 8.6). Petrographic units I–III are labelled. Lignite lithotypes: X – xylitic, gD – xylo-detrital (coarse detrital), dD – fine-detrital, G – gelified, KM – mineral-rich, M – minerite (marl, clay). Exceptional samples and those investigated by X-ray diffraction are numerically designated. Note portions of inorganic carbon ( $C_{inorg}$ ) versus the total carbon ( $C_{tot}$ ) on the right.

increase upwards. Exceptional samples are labelled and include: Fe (iron) mineralized xylite (samples 34, 40); Fe mudstone (37); fine organo-detrital carbominerite (58); carbominerite with limonite concretions (60), and marl (84).

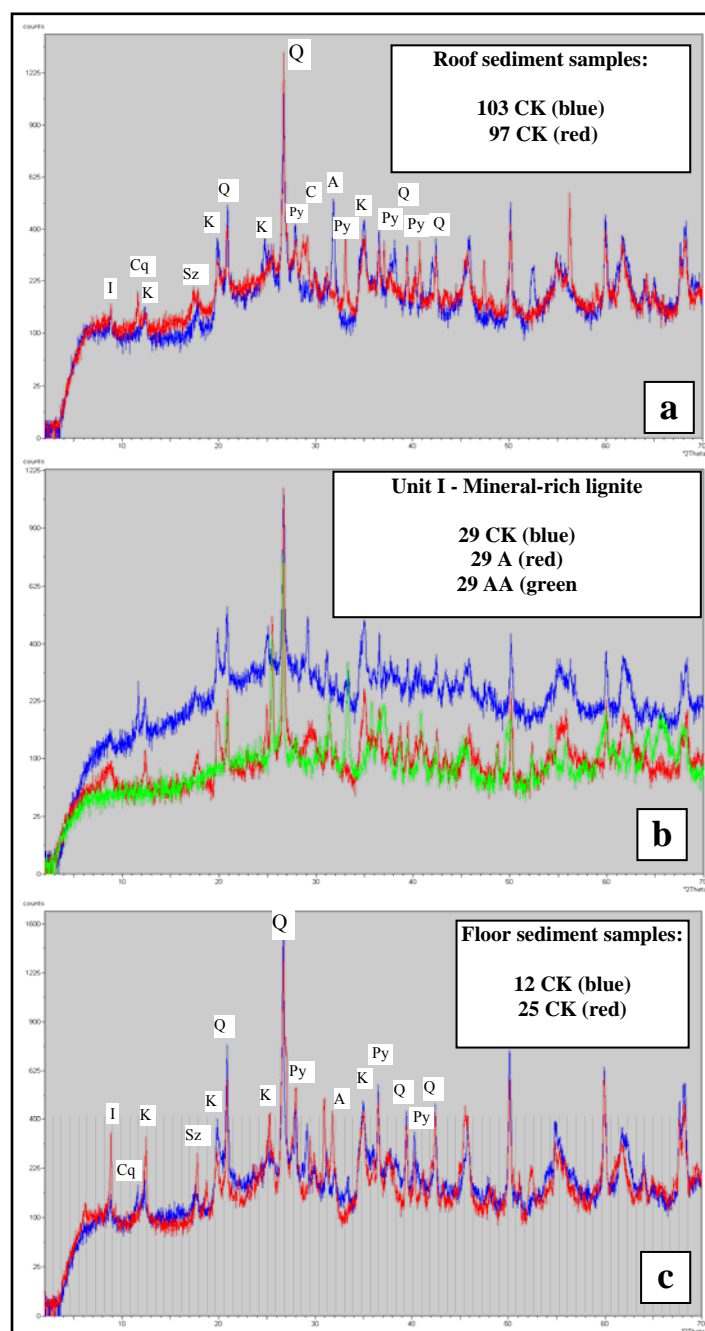
Another group of samples (68, 72, 73, 90, and 92) contains “abnormal” CaO contents. These samples include highly gelified lignite varieties (see MARKIČ & SACHSENHOFER, 1997, and at the end of **Chap. 6.4.1.4.5**). This interesting relation confirms the well known relation between Ca enrichment in a coal and its gelification degree (as a consequence of intense bacterial activity in an alkaline environment). The same Ca-rich and highly gelified samples are among low-ash and rank representative samples in **Tab. 7.1**. Another expected consequence of alkalinity’s governing biochemical processes in the upper part of the lignite seam would be a relative increase in sulphur content (see **Fig. 6.60**). But, this was not detected. Modes of sulphur occurrence (organic/inorganic affinity) and of its syn- versus epi-genesis should be investigated more in detail.

### 8.5.2. Mineralogical investigations

For some of the samples labelled in **Fig. 8.3** (see the column for  $\text{SiO}_2 + \text{Al}_2\text{O}_3$ ), mineralogical investigations were carried out by Miha MIŠIČ using X-ray diffraction. He kindly permitted us to use the results in this monograph. Semi-quantitative mineralogical data are presented in **Tab. 8.8**. A main significance of data in **Tab. 8.8** is that they involve samples of whole rocks (or whole coals) labelled “CK”, as well as samples of low-temperature (“A”) and high temperature ashes (“AA”). In this context even more illustrative than data in **Tab. 8.8** are diffractograms presented in **Figs. 8.4 to 8.8**, which show not only the peaks of minerals but also crystallinities of more versus less mineral-rich materials. Mineralogical investigations were up to date not performed at a large scale in the petrological study of the Velenje lignite, therefore the presented results are of a preliminary character.

**Tab. 8.8:** Mineral composition by X-ray diffraction of selected samples. Minerals are listed from left to right according to relatively decreasing abundances. Highly predominant minerals are highlighted (bold). Lithologic designations refer to megascopic descriptions. Sample abbreviations: CK – whole rock if non-coal lithology and whole coal if lignite lithology, respectively; A – low temperature (ca 400 °C) ash; AA – high temperature (ca 900°C) ash. (Mineral composition is given with permission of M. MIŠIČ, 2008).

Sample	Unit	Lithol. Designation	Mineral composition (highly prevailing in bold)
103 CK	Roof sediments	Argilite	<b>Quartz, kaolinite</b> , illite, siderite
97 CK		Argilite	<b>Quartz, kaolinite</b> , illite, calcite, gypsum, pyrite
84 CK	Lignite seam	Marl	<b>Calcite</b> , dolomite
72 CK		Ca-rich lignite	(Quartz, gypsum, pyrite))
72 A			<b>Quartz, anhydrite</b> , illite, hematite, siderite
72 AA			Anhydrite, hematite, maghemite, feldspars
34 CK		Fe mineralization after xylite	<b>Siderite</b> , Mg-calcite
34 A			<b>Hematite, maghemite, siderite</b> , Mg-calcite
29 CK		Mineral-rich lignite (carbominerite)	<b>Quartz, kaolinite</b> , illite, gypsum, pyrite
29 A			<b>Quartz, anhydrite</b> , illite, hematite, siderite
29 AA			Anhydrite, quartz, hematite, maghemite, illite, plagioklase
25 CK	Floor sediments	Argilite	<b>Quartz, kaolinite</b> , illite, chlorite, siderite, plagioklases, dolomite
12 CK		Argilite	<b>Quartz, kaolinite</b> , illite, gypsum, feldspars, dolomite, siderite, pyrite



**Fig.8.4:** X-ray diffractograms (XRD) of samples from **a)** roof sediments, **b)** mineral-rich lignite from unit I, and **c)** floor sediments from borehole P-9k/92.

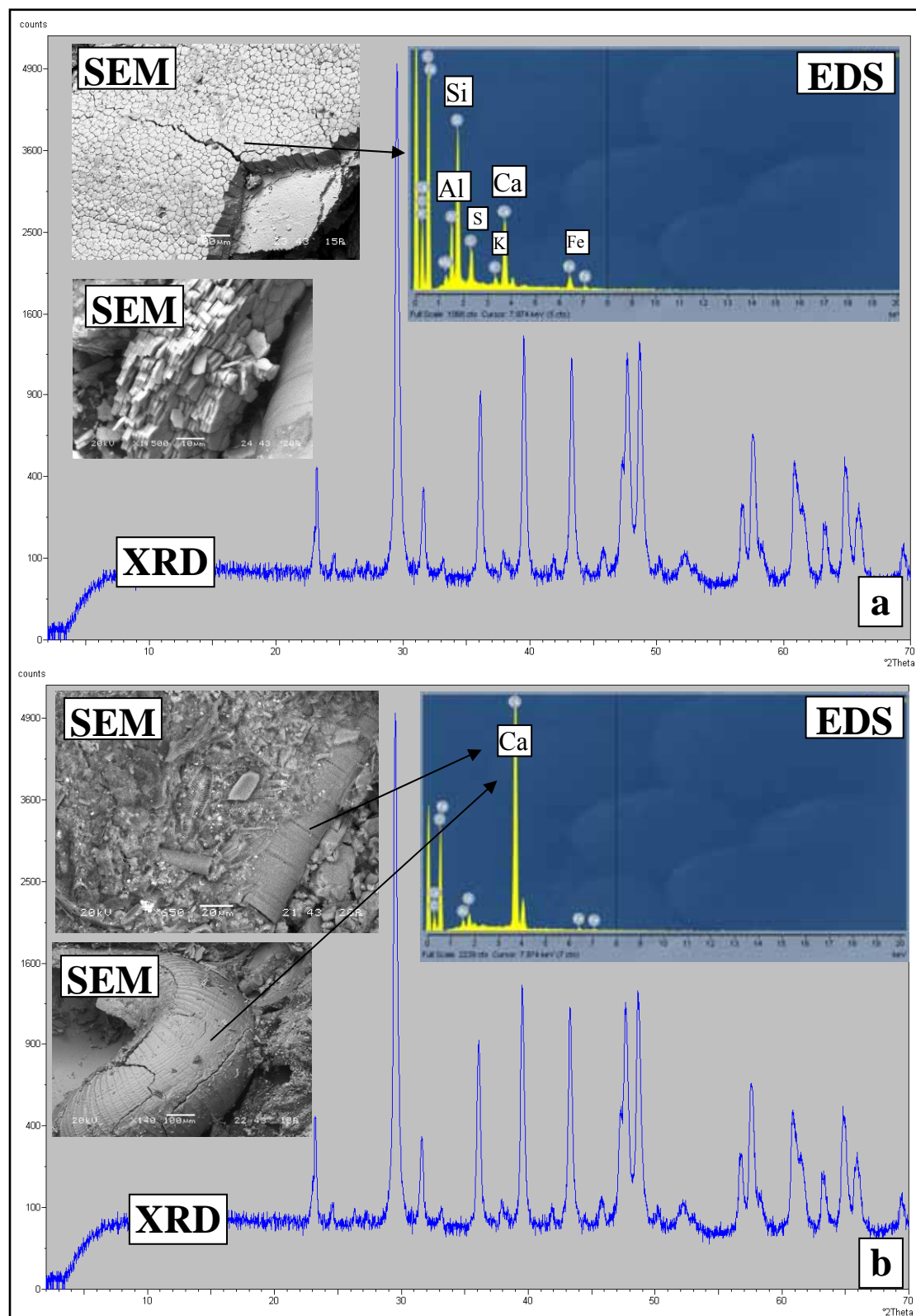
Argillite<sup>39</sup> (samples 103, 97, 12, and 25) is mainly composed of quartz and kaolinite. Illite is highly subordinated (as also evident by the low  $K_2O$  content from geochemical analysis). Other minerals cited in **Tab. 8.8** as siderite, calcite, gypsum, pyrite are present in low quantities in the roof sediments, whereas in the floor sediments chlorite, feldspars, and dolomite are also present.

Ashes (A and AA) of the mineral-rich lignite sample 29 are composed of quartz and kaolinite. Very subordinated are illite, pyrite and gypsum. Diffractogram of the "whole lignite" (29 CK) shows quite well crystallinity of this high-ash (39 % db) coal material.

Abbreviations for minerals:

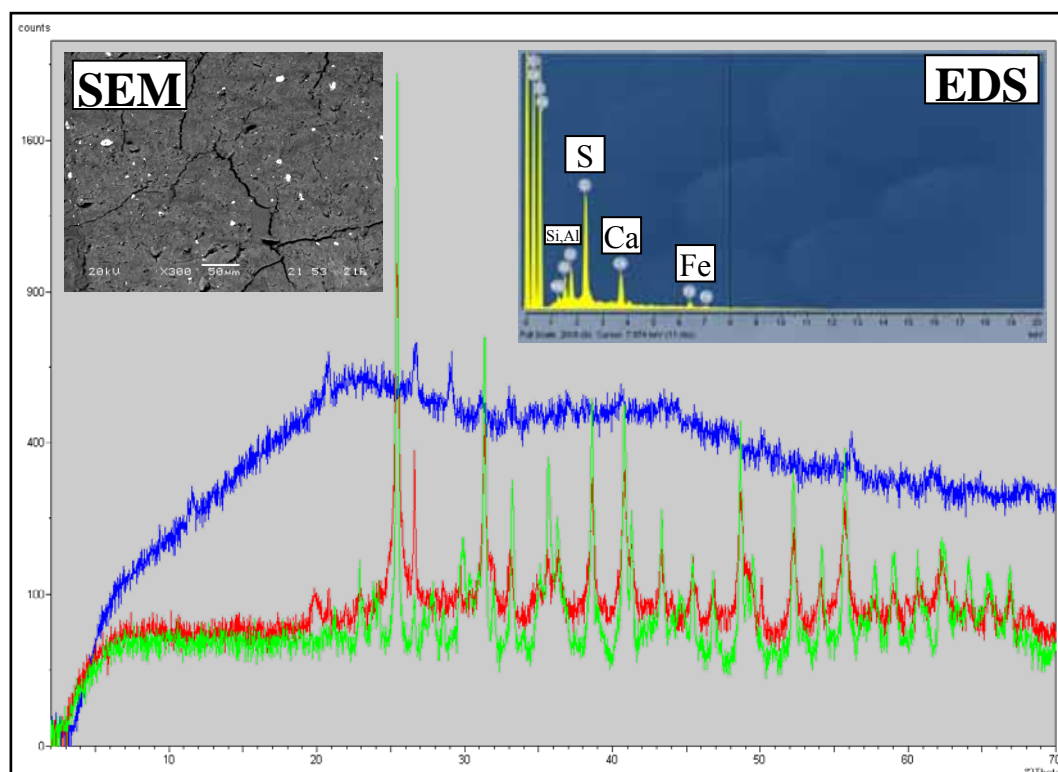
I=illite; Ca=calcite; Sz=szmolnokite; Cq= coquimbite; K=kaolinite; Q=quartz; Py=pyrite;  
(peaks of minerals have been identified with the help from WARD (1989, Fig.2).

<sup>39</sup> The term "argillite" (derived from a well known term "carbargillite" which contains by definition (e.g. Taylor et al., 1998; p.287) 20-60 vol.% of clay minerals) is used here for sediments with more than 60 vol.% of clayey-silty mineral matter.

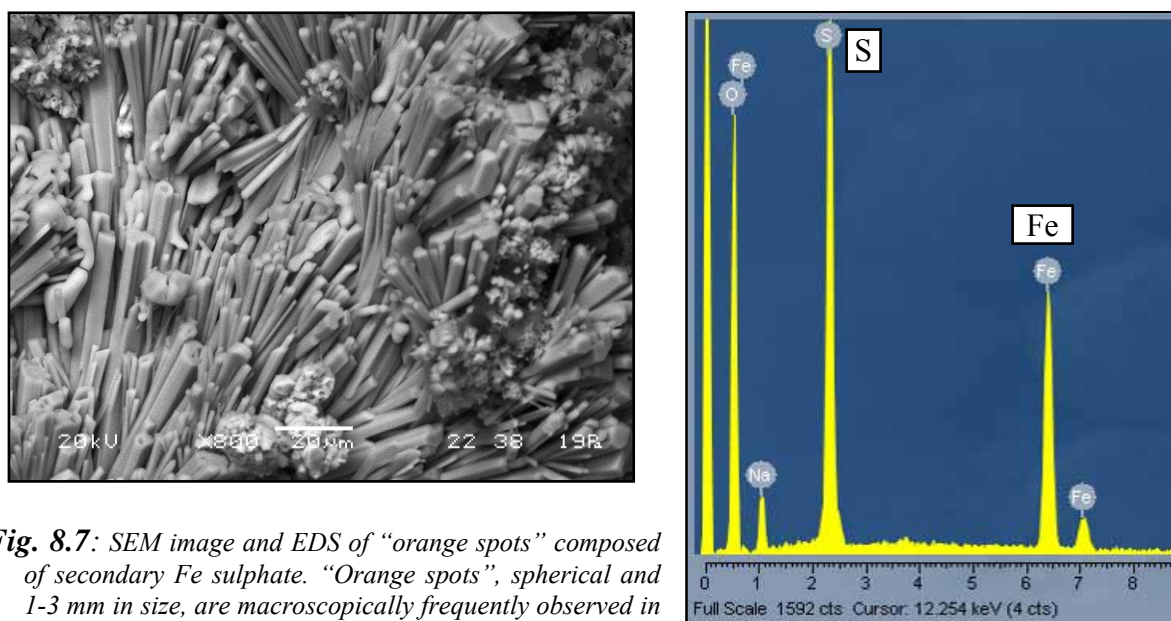


**Fig. 8.5:** Scanning electron microscopic (SEM) images, energy dispersive spectra (EDS) and X-ray diffractogram (XRD) of the marl sample 84 CK from unit III-a of the P-9k/92 lignite seam profile. Both diffractograms refer to the same powdered sample and show pure calcite. SEM pictures above (**Fig. 8.5-a**) show desiccated "pillow"-like structure of marl – in a plan view and perpendicular to the bedding. Si and Al peaks in EDS refer to clayey admixture thinly covering marl's bedding plane. SEM pictures below (**Fig. 8.5-b**) show Ca-rich fragments of molluscs.

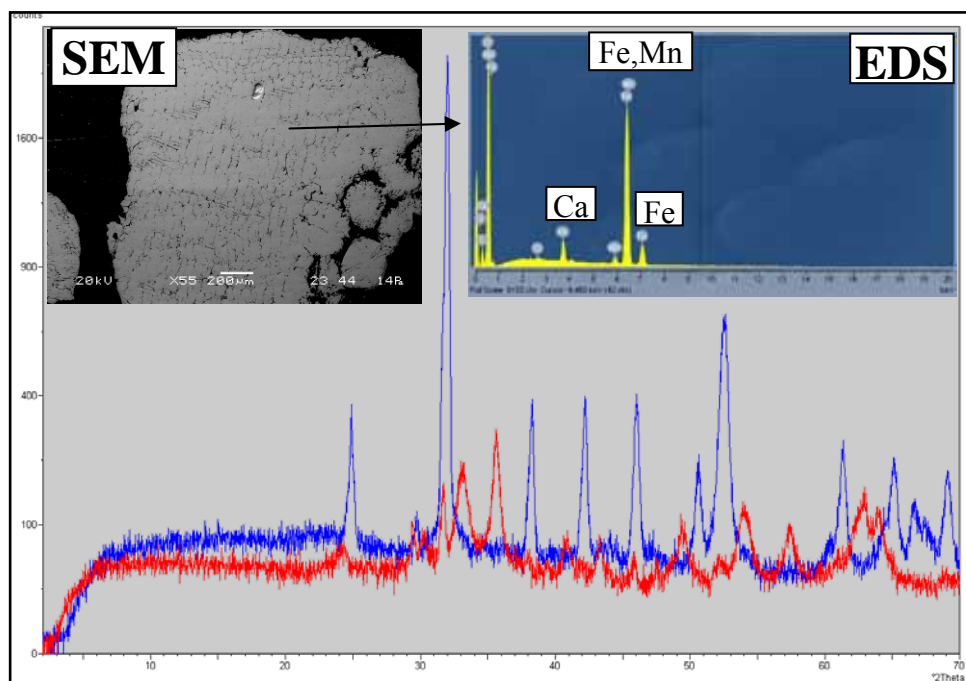




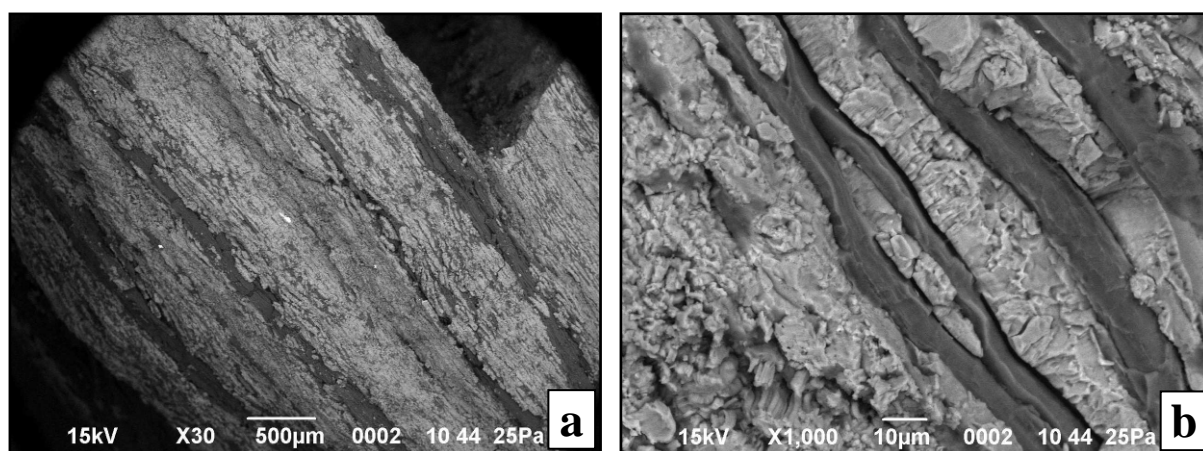
**Fig. 8.6:** SEM image, EDS and XRD (in blue) of Ca-rich low-ash (9% db) whole coal sample 72 CK. Beside Ca, Si and Al, Fe and S are detected in the EDS. Fe and S form mostly pyrite (or marcasite), which is visible as very bright spots in the SEM image. The lignite is fine-detrital, of prevailing densinite maceral composition and gelification index as high as 3.50 (see **Tab. 6.14**). The content of inorganic carbon ( $C_{inorg.}$ ) is negligible in this sample (**Tab. 8.1**), therefore Ca is considered to be organically bound. The crystallinity of whole lignite (blue XRD) is low, but peaks of quartz, gypsum and pyrite can be recognized. Red and green XRDs are for samples 72 A and 72 AA. High-temperature ash sample 72 AA (in green) exhibits somewhat better crystallinity than the low-temperature ash sample 72 A. For mineral composition see **Tab. 8.8**.



**Fig. 8.7:** SEM image and EDS of “orange spots” composed of secondary Fe sulphate. “Orange spots”, spherical and 1-3 mm in size, are macroscopically frequently observed in fine-detrital lignite, especially when exposed for a certain time to the atmosphere (e.g. in borehole-cores). Fe sulphate minerals known in coals are coquimbite and szmolnokite, if containing Na (as detected in the above EDS) also natrojarosite. The sulphates originate primarily from sulphides.



**Fig. 8.8:** SEM image, EDS and XRD (blue) of the Fe-rich, high-ash (62 % db) lignite sample 34 CK. The red XRD refers to the low-temperature ash sample 34 A composed of hematite, siderite and Mg-calcite. Sample 34 CK (blue XRD) was defined to be composed of siderite (**Tab.8.8**), very probably also of ankerite as detected by Ca presence in EDS. The SEM image clearly shows that Fe mineralization entirely replaced the cellular structure of xylite.



**Fig. 8.9:** SEM image of a calcified xylite (sample from underground mine workings). **a)** A general view, **b)** calcite crystallization within “channels” (tracheids) of the wood tissue. Dark bands are lignin rich cell-walls.

### 8.5.3. Trace-element geochemistry

Original results of trace-element geochemical analyses are presented in **Tabs. 8.2** and **8.3**. These analyses were done on whole lignite samples and are as thus treated also in the continuation. They were not recalculated to the pure inorganic basis, nor was the affinity of their bonding studied more in detail by the float-and-sink analysis. **Tab. 8.9** presents ranges expressed by minimum to maximum contents of separate trace elements within the lithofacies units along the P-9k/92 lignite seam profile. Exceptional samples characterized by

extraordinary high  $\text{Fe}_2\text{O}_3$  or CaO contents (**Fig. 8.3**), which contain also either outstandingly high or outstandingly low contents of separate trace elements, are not included into the mentioned ranges. Exceptional samples are cited at the bottom of **Tab. 8.9**.

In **Tab. 8.9**, the elements are cited from the left towards the right side in the order of generally decreasing contents, from Ba and Sr with contents as high as above 200 ppm, to Se, Cd, and Hg with contents below 3, 1, and 0.3 ppm, respectively. One deficiency of the presented trace element analysis is that B, an outstanding paleo-salinity indicator, was not analyzed. Also Ge, an element known by its affinity to organic bonding, was not included into the analytical package.

In the upper part of **Tab. 8.9** some averages and ranges of contents of trace elements from literature are cited, referring to:

- soils of the world (from TAYLOR et al., 1998, p.272 – after SWAINE, 1990 and BOWEN, 1979),
- soils of Slovenia (ANDJELOV, 1994)
- coals of the world (from TAYLOR et al., 1998, p.272 – after SWAINE, 1990 and BOWEN, 1979; from VALKOVIĆ, 1983, p.59 – after U.S. National Committee for Geochemistry., 1980; and from KETRIS & YUDOVICH, 2009),
- coals of the USA (from VALKOVIĆ, 1983, p.59 – after U.S. National Committee for Geochemistry., 1980;

Already a brief overview of trace-element data for the Velenje lignite in **Tab. 8.9** shows that abundances of the great majority of trace elements in the treated lignite profile are more or less “normal” in comparison to the world coals, to the world soils, as well as to the soils in Slovenia. Two exceptions are U and Mo, which are moderately enriched in the Velenje lignite.

As is generally visible from **Tab. 8.9**, abundances of the majority of trace elements in the studied lignite are lower than in the floor and the roof sediments, respectively. Also within the lignite seam, contents of trace elements mostly decrease from the lower (ash-rich) toward the upper (lower-ash) part of the seam. However, two groups of elements are slight exceptions in this sense. The first group is Ba, Sr, and Zn, and the second is As, U and Mo.

Ba, Sr, and Zn are slightly depleted in the two mid-seam units II-b and/or II-c. Somewhat higher contents of these elements, both in ash-rich units I and II-a below and in ash-poor units III-a and III-b suggest a conclusion, that these elements can be bound both organically and inorganically. Organic affinity of Ba and Sr was for example clearly proved for the Trbovlje brown coal (UHAN, 1993). In the case of the Velenje lignite much more pronounced is the inorganic bonding of Ba and Sr because, for example, both elements are depleted even in samples 68, 72, 73, 90 and 92 which are very low in ash yield. In comparison to “whole lignite” samples, Ba and Sr are enriched in the marl band (sample 84) in the upper part of the coal seam. This is clear evidence of their well known affinity to bonding into the calcite structure (replacement of Ca ions). Zn is enriched in the  $\text{Fe}_2\text{O}_3$ -rich samples as well as in the previously mentioned marl band. Ni is characteristically enriched only in one  $\text{Fe}_2\text{O}_3$ -rich sample (sample 34). All other elements in **Tab. 8.9** are relatively depleted in the “exceptional” samples.

**Tab. 8.9:** Ranges of trace element contents (in ppm; for Au in ppb) of whole rock / whole coal samples (CK) from the floor sediments, from the lignite seam and from the roof sediments in the P-9k/92 profile (range values are reasonably rounded). Values for samples with extreme contents of Fe<sub>2</sub>O<sub>3</sub> and CaO (**Fig. 8.3**) - and at the same time with extreme contents (either high - in bold, or low) of considered elements - are not included into ranges (data source: **Tab. 8.2** and **8.3**; for Ba and Ni also **Tab. 8.1**). Considered averages are the following:

SW – soils worldwide (from TAYLOR et al., 1998; p.272; after SWAINE, 1990, and BOWEN, 1979)

SSlo – soils of Slovenia (ANDJELOV, 1994)

CW<sup>1</sup> – coals worldwide (from TAYLOR et al., 1998; p.272; after SWAINE, 1990, and BOWEN, 1979)

CW<sup>2</sup> – coals worldwide (from VALKOVIĆ, 1983, p.59; after U.S. Nat. Comm. for Geochem., 1980)

CW<sup>3</sup> – brown coals worldwide (from KETRIS & YUDOVICH, 2009)

CUSA – coals of USA (from VALKOVIĆ, 1983, p.59; after U.S. Nat. Comm. for Geochem., 1980)

	Ba	Sr	Zn	V	Rb	Zr	Ce	Ni	La	Cu	Y	Nd
<i>Some averages</i>	100-3000	50-1000	10-300	20-500	20-1000	60-2000	-	5-500	2-180	2-100	10-250	-
	371	98	113	118	-	49	-	53	31	28	18	-
	20-1000	15-500	5-300	2-100	2-50	5-200	-	0,5-50	1-40	0,5-50	2-50	-
	500	500	50	25	100	-	12	15	10	15	10	-
	150	120	18	22	10	35	22	9	10	15	8,6	-
	150	100	39	20	2,9	30	8	15	6	19	10	-
Velenje lignite – P-9k/92 profile	Roof sedim.											
	180-310	58-145	70-100	125-155	100-130	80-100	45-65	30-40	20-30	20-30	20-30	20-30
	III-b	50-140	6-20	20-35	10-35	10-20	7-17	5-9	4-9	6-11	3-7	4-9
	III-a	90-180	8-18	25-35	20-35	15-20	9-18	5-9	5-9	7-11	4-6	6-11
	II-c	50-105	5-12	20-45	15-35	10-25	8-20	6-10	5-11	7-12	5-10	4-10
	II-b	65-90	10-30	35-45	25-60	20-30	15-20	10-30	10-12	9-15	8-9	7-12
	II-a	90-130	30-45	45-55	40-55	25-40	18-35	15-40	10-20	13-20	10-13	10-17
	I	120-230	45-55	50-80	40-65	30-45	25-40	15-35	15-20	15-25	12-20	12-20
	Floor sedim.	250-415	50-260	100-200	80-130	55-160	50-85	25-65	30-45	25-40	20-40	25-40
		34, 37, 40,		34, 37, 40,	34, 37, 40,	34, 37, 40,	34, 37, 40,	34, 68, 72,	34, 37, 40,	34, 37, 40,	34, 40, 58,	34, 37, 40,
Not included samples		58, 60, 68,		58, 68, 72,	58, 60, 68,	58, 68, 72,	58, 68, 72,	73, 84, 90,	58, 68, 72,	58, 60, 68,	68, 72, 73,	58, 60, 68,
		72, 73, 84,		73, 84, 90,	72, 73, 84,	73, 84, 90,	73, 84, 90,	92	73, 84, 90,	72, 73, 84,	84, 90, 92	72, 73, 84,
		90, 92		92	90, 92	92	92		92	90, 92		90, 92

Tab. 8.9 – continuation

	Pb	Ga	As	Co	Th	Cs	U	Mo	Se	Cd	Hg	Au (ppb)
<i>Some averages</i>	<i>SW</i>	5-70	1-50	1-40	1-35	0.3-20	0.7-9	0.2-5	0.1-2	0.02-10	0.01-0.5	1-20
	SS <sub>lo</sub>	-	8	28	8.5	-	3.3	-	-	1.16	-	-
	<i>CW<sup>d</sup></i>	1-20	0.5-80	0.5-30	0.5-10	0.3-5	0.5-10	0.1-10	0.2-10	0.1-3	0.02-1	<10
	<i>CW<sup>e</sup></i>	7	5	5	-	-	1	5	3	-	0.012	-
	<i>CW<sup>f</sup></i>	5.5	7.6	4.2	3.3	0.98	2.9	2.2	1.0	0.24	0.10	3.0
	<i>CUSA</i>	16	15	7	2	0.4	1.6	3	4	1.3	0.18	-
Velenje lignite – P-9k/92 profile	Roof sedim.	15-25	5-8	14-18	10-13	7-11	2-4	1-4	1-3	<0.4	<0.15	<1
	III-b	4-9	3-7	2-3	1-4	1-3	5-11	7-13	<1.0	<0.2	<0.10	<2
	III-a	5-10	5-8	2-3	1-3	2-4	8-13	8-20	<1.5	<0.1	<0.10	<3
	II-c	8-16	7-12	2-4	1-4	1-4	10-13	5-13	<1.5	<0.3	<0.10	<2
	II-b	8-15	10-12	3-5	2-5	2-4	9-13	9-15	1-2	<0.2	<0.20	<2
	II-a	15-25	13-25	4-7	3-6	3-6	9-12	9-15	1-2	<1.0	<0.20	<3
	I	10-25	13-25	4-9	4-8	3-7	8-14	5-12	1-3	<1.0	<0.25	<2
	Floor sedim.	15-40	10-20	10-20	10-15	7-13	3-14	1-10	1-3	<1.1	<0.30	<2
	Not included samples	34, 37, 40,	25, 34, 37,	34, 37, 40,	34, 37, 40,	34, 37, 40,	34, 37, 40,	40, 8	25, 34, 37,			
		58, 60, 68,	40, 58, 84,	58, 60, 68,	68, 73, 84,	58, 60, 68,	34, 37, 40,		40, 68, 72,			
		72, 73, 84,	90, 92	72, 73, 84,	90, 92	72, 73, 84,	60, 84		73, 84, 90,			
		90, 92		90, 92		90, 92			91, 92			

Contents of As, U, and Mo in the lignite in the investigated P-9k/92 profile are approximately equal to those in the floor and the roof sediments, or are even slightly higher. Contents of As are decreasing from the ash-rich bottom part of the lignite seam (where they vary between 13 and 25 ppm) towards ash-poor top of the seam, where they fall below 10 ppm. This trend indicates inorganic bonding. Arsenic in coals is mostly considered to be connected with pyrite/markasite or even arsenopyrite. But a clear correlation between the mentioned sulphides and As content was not detected. The same is true for the correlation between sulphur contents and As contents. One explanation can be the difference in modes of occurrence of the two elements. Namely, on the basis of preliminary (few samples) isotopic investigations of S in different lithotypes of the Velenje lignite it was found that the majority of sulphur is bound organically (ŠTURM et al., 2009). In comparison to the ranges and averages for coals and soils as cited in **Tab. 8.9** (top rows), As in the Velenje lignite is comparable to them, or is slightly more abundant. The lower part of the seam is somewhat more problematic. Arsenic can be of concern in coal use, because it is highly volatile, like for example Hg<sup>40</sup>.

U in contents of up to 15 ppm, and Mo in contents of up to 20 ppm are equal or greater by their abundance within the lignite seam than in the floor sediments. Along the seam profile, both are relatively stable in contents, indicating a relative independency of the mineral–matter content of lignite (and a syngensis referring to peat formation). The contents of both elements are very significantly lower in the roof stratum just above the lignite seam (which is still Si+Al characterized, but is soon upwards replaced by a marl bed with molluscs). The independence of U and Mo contents from the lignite composition (from its mineral versus organic matter content) may be explained by the fact that the fixation of both elements, either organic or inorganic, is crucially dependant on pH-eH conditions. Acidity (pH) conditions slightly changed during peat accumulation in a way that the peat-forming environments became slightly more and more alkaline (inferred from a slight CaO increase and SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> decrease). However, even in presumably outstanding alkaline environments as e.g. interpreted on the basis of exceptionally Ca-rich samples (68, 72, 73, 90, 92), U and Mo contents are not changed considerably. They are only clearly depleted in the Fe<sub>2</sub>O<sub>3</sub>-C<sub>inorg.</sub> (siderite)-rich samples 34, 37 and 40 (Mo only in 40) (**Tab. 8.9** – bottom), and in calcite-rich marl sample 84. Because siderite is well known to be stable at moderate oxidation-reduction potential (eH) relative to pyrite which is stable at lower eH values, reducing conditions seem to be a very decisive factor of non-mobility of U and its fixation. Another factor, alkalinity in an eutrophic realm, seems to be decisive indirectly. It enhances bacterial activity and hence the decomposition of organic matter. This process, the more intensive it is, together with the consumption of any dissolved oxygen from percolating waters, causes that the peat-forming environment is permanently reducing. The non-variability of U content throughout the lignite profile indicates that the redox potential (and the processes influencing it) did not change considerably during the peat formation.

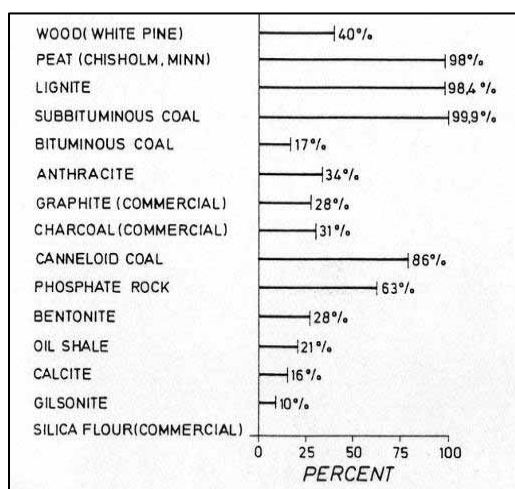
In comparison to the ranges and averages of U contents in “regional” coals and soils as cited in **Tab. 8.9**, U contents in the Velenje lignite can be considered as moderately higher, but not “alarming”. Widespread areas of different lithologies with higher contents of these elements are known in the world as well as in Slovenia. However, because the lignite is exploited and burnt, transformed from its natural position and state, and its ash even used for industrial

<sup>40</sup> Well known from the literature are As-rich coals in some provinces in China, e.g. in arsenosis endemic area of the Guizhou Province where coals with As contents as high as from 10 to 35 grams As per kilogram coal are reported (DING et al., 2001; LIU et al., 2002).



products (cements, building elements), care must be taken in respect to potential negative environmental and health impacts due to this lignite use.

An average U content of coals worldwide is as low as only 1–3 ppm and most coals worldwide do not contain more than 10 ppm U (**Tab. 8.9** and references there-in). But, there are coals which contain up to 100 ppm, exceptionally even more than 1000 ppm U (e.g. VALKOVIĆ, 1983). An interesting aspect is also that the extraction of U from solution is much higher, almost total, in the case of low-rank coals (due to their higher chemical activity) than in the case of “inert” higher rank-coals (**Fig. 8.10**). The bonding of U into peat, lignite or subbituminous coals is therefore a process running especially during the biochemical phase of the coalification process, whereas it ceases in the proceeding physical-chemical stage of coalification.



**Fig. 8.10:** Percent of uranium extracted by coal and other materials from uranyl sulphate solutions containing 200 ppm uranium (copied from VALKOVIĆ, 1983, p.176; after MOORE & STEPHENS, 1954). Experiments were done with powdered samples at low (<3) pH values.

Concerning the petrographic constituents of coal and U fixation, several studies from the USA are mentioned by VALKOVIĆ (1983). These studies mostly showed that no tight correlations exist between the lithotypes and/or maceral composition and U occurrence. However, in Velenje, a very contrasting difference in radioactivity between fine-detrital and xylite-rich lignite has been detected recently. Radioactivity was measured by natural gamma-ray spectrometry in one horizontal underground borehole (MAURER et al., 2008). Since this effect was encountered up to the present in only one borehole, further petrographic and in-well geophysical investigations are expected to clarify this relationship with higher accuracy.

As the source of U (and of Mo which is often mentioned to be associated with U), andesite volcanoclastics building up the southern hinterland of the Velenje basin as well as somewhat more distant massifs of tonalites, granodiorites and metamorphic rocks building up the Karavanke mountains and the Pohorje massif can be considered as the most probable.

Searching for economic concentrations of U in coals was a great worldwide effort in the 1950 and the 1960s, but no really significant production of uranium from coal was realised afterwards. Coal ashes were somewhere used as a radioactive energy source material, but clear information is still now not easy to be achieved (mostly due to strategic and political reasons). Besides coals, organic-matter-rich sediments in general may host increased U concentrations in deposits of the so called coal- and oil-shale type (DILL & SACHSENHOFER et

al., 2008). U-rich carbonaceous rocks of the Late Carboniferous and Permian age were explored and exploited in central Europe e.g. in the Lower Silesian Basin in Poland, Bohemian basin (Czech Republic), Döhlen, Stockheim, Weiden, Oos-Saale and Saar-Lorraine basins in Germany and near St. Hippolyte in France (DILL & SACHSENHOFER et al., 2008 – and references there-in).

In former Yugoslavia, U exploration started already at the end of the 1940s with the consideration that especially some specific coals could be perspective as U-bearing (FLORJANČIČ, 2002). Indeed, especially in the Dinarides, which are by far predominantly composed of Mesozoic carbonates, numerous coals in Tertiary basins – especially those lying the closest to the carbonates – were detected as U-enriched. In the territory of southern Slovenia and Istria in Croatia U-enriched coals are known from the following localities: Vremški Britof, Sečovelje, Kočevje and Kanižarica in Slovenia, and the Istria coals with Raša as the best known among them in Croatia (HAMRLA, 1959; OMALJEV, 1971; FLORJANČIČ, 2002; MARKIČ et al., 2007) (see **Fig. 2.1** for locations and rank, and **Chap. 4.5** for some more data about the Kočevje and Kanižarica coals). FLORJANČIČ (2002, p.243) writes that the highest concentration of U in coals in Slovenia was found in ash of the Vremški Britof coal – 0.5 %. None of the above mentioned coals is exploited anymore and from none of them U was exploited. Some mines of these coals were closed in the 1960s and 1970s and the last of them in the 1990s. All these coals were rich in sulphur. Maximum sulphur contents occurred in Vremški Britof, Sečovelje, and Raša with *Stotdaf* contents up to 12 % (HAMRLA, 1959).

In the 1960s exploration for U in Slovenia reoriented mainly to clastic rocks of the Permo-Carboniferous and Triassic age, especially into sandstones of the Val Gardena/Gröden formation of the Permian age. In this formation, the Žirovski Vrh U mine was opened and operated up to 1990 (FLORJANČIČ, 2000). Interestingly, also in Žirovski vrh, U mineralisation is tightly connected with organic matter – especially with fossil wood trunks of the anthracite coal rank, which are embedded within fluvial sandstones (see also **Chap. 6.1** and references there-in).

## 9. FINAL DISCUSSION AND CONCLUSIONS

### 9.1. General geological setting

The Velenje lignite seam is located approximately in the middle of the more than 1000-m-thick freshwater clastic sedimentary complex of the Pliocene and Plio-Quaternary age which occupies the intermountain Velenje basin situated between the Karavanke Mountains and the Savinja Alps in northern part of Slovenia (**Figs. 2.2, 2.3, 2.4**). The basin is 15 km long and up to 4 km wide. Pre-Tertiary basement, mainly composed of Triassic limestones and dolostones, is more than 2000 m deep in the central part of the basin. On the surface, Mesozoic carbonates build up the northern and western mountainous hinterland up to the heights of 1600 m above the sea level. Another vast lithologic complex is andesitic tuff to the south of the basin. Both complexes are in tectonic contact below the Pliocene sedimentary fill. Regarding the Pliocene lignite-bearing sedimentary fill of the basin, these two complexes are important because they represented, together with some other lithologies in the wider area, source rocks for the Pliocene sedimentary input. They were also important because they had a decisive influence on the geochemical characteristics of the peat-forming milieu (elemental composition, nutrients, pH) which considerably governed biochemical processes of early diagenesis of the peat matter.

The basin is bounded by two regional dextral strike-slip faults, the Smrekovec fault to the north and the Šoštanj fault to the south (**Fig. 2.2**), both belonging in a wider sense to the Periadriatic fault system. Both faults are still active at the present. To the east, they are displaced by the Lavanttal (Labot) fault.

There is a significant number of coal-bearing pull-apart basins in the Alpine region – what is unique in the case of the Velenje basin is the great thickness of the Pliocene lignite seam. It is 60 m thick on average, but can reach a thickness of more than 150 m. Besides geometry (length 8.3 km, width up to 2.5 km, thickness up to 165 m, and the shape of a “mega bowl”), high ash yield (especially at the bottom of the seam), petrographic heterogeneity, remarkably high sulphur content, calcification of plant remains and gelification effects are other remarkable features of this lignite seam.

### 9.2. Initiation, development and termination of the peat formation

Pull-apart (and rift) basins are typically characterized by very high initial subsidence rates (e.g. LAMBIASE, 1990; MCCABE, 1991; GRUBER & SACHSENHOFER, 2001; SACHSENHOFER et al., 2003; OPLUŠTIL, 2005; PREMUR, 2005). During early stages of basin formation, the resulting depression is filled with fluvial sediments. If subsidence exceeds sediment input, the fluvial environment is replaced by a lacustrine one. Given favourable climatic and vegetation growth conditions, a swamp may form during the transition from the fluvial to the lacustrine environment, which gives rise to a single, often a thick lignite/coal seam. When subsidence

rates decrease, the formed tectonic lake will be filled by deltaic sediments. Because of the gradual shallowing of the lake, the deltaic succession typically shows a coarsening upward trend. One or more additional lignite/coal seams may form during the final stages of the filling of the lake in deltaic environments.

The sedimentary fill of the Velenje basin fits this model very well. Fluvial sediments form the lower part of the Pliocene succession. They show a fining upward trend with coarse clastic sediments at the base and fine-grained sediments (clay, silt) with subordinate sands and gravel lenses in its upper part (**Fig. 2.3**). The latter has been deposited in a low-energy environment with meandering streams, crevasse splays, and floodplains (compare **Fig. 4.1**).

When the subsidence rates continued to exceed sediment accumulation, the fluvial environment was replaced by a lacustrine environment. The main Velenje lignite seam formed during the transition stage. Fluvial processes influenced the deposition of the ash-rich lower part, whereas its upper part has been mainly influenced by lacustrine processes. A short-term flooding of the peatland by a lake is indicated i.a. by a mollusc-rich marly sediment (0.5 m thick in P-9k/92 and adjacent boreholes) (**Figs. 2.4, 6.22**), which occurs about 15 m below the top of the seam. Well correlation suggests that this lake was laterally restricted, mostly extending from the central part of the basin toward north. A general decrease in the abundance of xylitic coal from bottom to top (e.g. **Figs. 6.22, 6.23, 6.24**) suggests a vegetation rich in trees during accumulation of the fluvial-controlled lower part of the seam and a prevalence of bush and reed vegetation during deposition of the upper part of the seam. Whereas coals formed along the shorelines of lakes are often rich in ash, the upper part of the Velenje lignite seam is relatively clean. Perhaps this is because the aerial extension of lakes in the Velenje basin was limited during the final stages of peat accumulation. Only the uppermost lignite layers in borehole P-9k/92 show an increase in ash, which is typical for coal in a transgressive setting.

The outstanding thickness of the Velenje lignite seam indicates that peat accumulation was in equilibrium with subsidence for several hundred thousands of years (see discussion in **Chap. 4.4**). Although stages with slightly different subsidence rates might have occurred during peat accumulation, it is important to note, that the huge thickness of the coal is a result of a single high-subsidence event.

The top of the lignite seam is sharp and overlain by fine clastics, silty clay and/or by a distinct marl bed with molluscs (**Figs. 2.4, 6.22, 6.24**). This suggests that peat accumulation was terminated by a rapid relative rise in water (lake) level. Probably this is due to an increase in subsidence. Compaction of the thick peat layer may have also played a role. In theory peat accumulation might have been terminated due to a climatic change. However, there are no paleofloristic indications for such a change.

After the termination of peat accumulation, lacustrine environments prevailed in the Velenje basin. Fine-clastic lacustrine sedimentation was occasionally interrupted by deltaic progradations depositing sand-gravel bodies within the predominating silty clayey strata above the main lignite seam (**Fig. 2.3**). For example, a more than 5-m thick fluvial gravel body was detected only 5 m above the lignite seam in borehole P-9k/92, (**Fig. 6.45-a**). The most prominent progradation of coarse-grained material was from the north and formed a broad “alluvial fan” (as termed by BREZIGAR, 1981), or fan delta. This progradation was active already in the time of peat accumulation and influenced the distribution of the peatland as well as the accumulation of biomass. In the northern part of the seam, e.g. at the site of

borehole P-8z/92 (**Fig. 2.4**), the lignite seam is highly split and interbedded by poorly sorted silts, sands and even gravels. Also the deviation of a more regular elliptical contour of the lignite seam in the north (**Figs. 1.1, 1.3, and 2.2**) is most probably the consequence of this clastic “intrusion” into the peatland.

At least one additional lignite seam occurs in the Velenje basin in lacustrine (?) sediments far above the main lignite seam. This is the seam, which was detected in the 18<sup>th</sup> century and which was mined during the 19<sup>th</sup> century (**Chap. 1.2**). Unfortunately, no detailed description of the geology of the high-ash lignite is available. However, it is reasonable to assume, that this seam formed during the filling stage of the lake, which formed after accumulation of the main seam in a deltaic environment. Limited thickness and lateral extension are typical for this type of coal, which formed in a regressive setting.

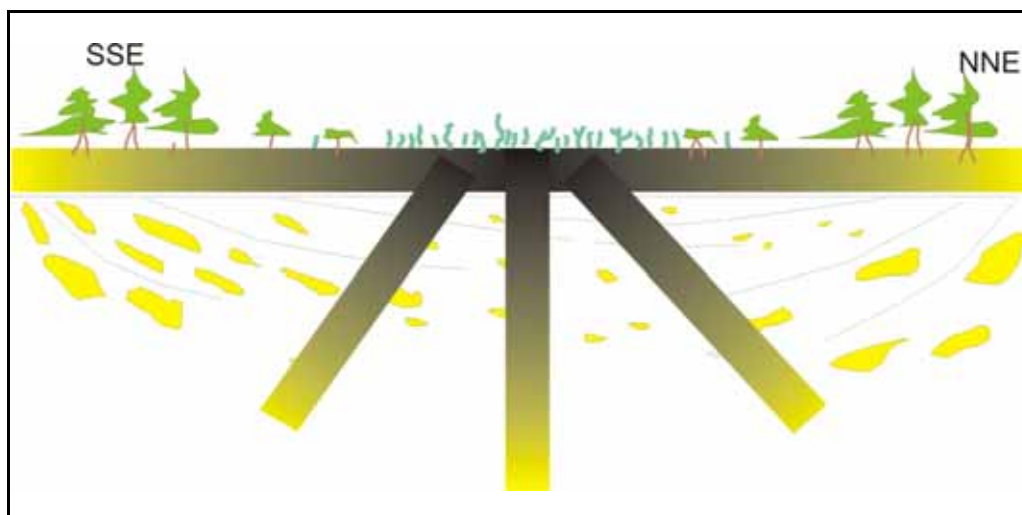
### **9.3. Lignite facies, segmentation of the seam, lithotype classification, and interpretation of the peat-forming environments on the basis of micro-petrographic indices**

Macrofacies variability of the lignite seam was studied on the basis of data from petrographic logging of lignite borehole-cores (**Chap. 6.3.2**) and on the basis of underground mapping of road-faces and long-walls (**Chap. 6.3.3**). This work revealed that the lignite is clearly and regularly stratified, the strata being differentiated by their lithotype composition, texture and internal structure. The thickness of more or less uniform strata ranges most often from some decimeters to not more than 2 or 3 meters. Internal deviations from parallel bedding, which often involve chaotically distributed xylite pieces, point out syn-depositional deformations caused by loading, sinking and gravitational sliding of heavier xylite-rich masses into a softer, lower lying fine-detrital organic sediment (e.g. **Fig. 6.28**). Such occurrences can be interpreted to reflect already originally labile zones, characterized by short-distance topographic dislocations. True post-depositional tectonical effects are visible as crushed-lignite zones, as dense systems of fractures, and as tectonic planes cutting not only fine-detrital matrix but also bigger xylitic pieces.

An important result of the underground mapping, especially in the Preloge sector between levels –80 to –110, was the revealing of gross spatial lithofacies pattern. With the supplement of data from the structural boreholes P-9k/92, P-12o/92, and P-11r/98, which penetrated the whole lignite seam, it was clearly revealed that xylite-rich lignite forms mainly the outer and the lower part of the seam whereas fine-detrital lignite prevails in the upper part and the vast lateral interior of the seam, respectively (**Fig. 6.36**). The inclination of strata – of 30–40° along the seam margin to gradually almost horizontal layering in the inner part of the basin (**Fig. 6.37**) – shows that the central part of the peat-accumulation was continuously subsiding and thus forming continuing accommodation space for further peat growth and accumulation.

Macro- and microscopic petrographic study of lignite in the reference borehole P-9k/92 revealed that the seam profile can be divided into three main units, termed as units I (lower part of the seam), II (middle part of the seam) and III (upper part of the seam) (MARKIČ & SACHSENHOFER, 1997). Unit II was further subdivided into subunits II-a, II-b and II-c, and unit III into subunits III-a and III-b. The lower units (and subunits) are broadly characterized by xylite-rich lignite, by high-ash lignite and dirty bands, by occasional Fe-mineralization, and by remarkable fusite, mainly in the form of encrustations over xylite pieces. By underground mapping, a similar appearance of lignite was detected at the periphery of the

lignite seam. Taking into account the already mentioned gradual decrease in strata inclinations of 30–40° toward the basin's centre at the margin of the lignite seam, to the horizontal layering in the centre, xylite-rich lignite of both sites belongs to the same starting phase of the tree-rich peat accumulation. A simplified illustration of this evolution is presented in **Fig. 9.1**. As the subsidence gradually continued (considerably due to compaction), enlarging open-water surfaces were developed in the vast interior of the peat accumulation area. It became gradually calmer and calmer, and less influenced by external sediment input. Such circumstances gave rise to a lignite type which is predominantly low in mineral matter, fine-detrital and markedly gelified.



**Fig. 9.1:** Very simplified illustration of the marginal tree-rich versus inner basin dwarf plant distribution as presumed in the development of the Velenje peat accumulation. Subsidence was the highest in the inner part of the basin, causing inclination of the strata at the margins and creating accommodation space in the interior.

To describe the lignite's composition (and facies, respectively), an original lithotype classification was created (MARKIČ et al., 2001) (**Figs. 6.8 and 6.10**). The leading idea in this coal lithotype classification was to apply, if possible, an already existing sedimentary classification which would possibly function well also in the case of lignite. As lignite clearly exhibits a fragmental/detrital appearance, the well known UDEN's scale was applied to describe size limits of the lignite's constituting components. Basic lithotype components of lignite were termed: detrite (D – composed of particles smaller than 1 mm), xylo-detrite (xD – fragments between 1 and 32 mm), detro-xylite (dX – fragments between 32 and 64 mm), and xylite (in three classes: X – 64–512 mm; XX – 512–2048 mm; XXX – larger than 2048 mm). Lithotypes are characterized by the contents of separate lithotype components (as for example clastites are defined by the contents of clay, silt and sand fractions). For the ranges of separate lithotype components, classes with 0–15, 15–40, 40–60, 60–85, and 85–100 % of one component in proportion to the other(s) have been applied. This division is similar to that which is well known for hard coals when describing ratios between bright and dull bands. The classification was tested by both core logging and underground mapping and is now used in the every-day praxis referring to the petrographic description of the Velenje lignite.

On the microscopic level, facies variability was studied by maceral analysis, most systematically in the P-9k/92 lignite-seam profile (MARKIČ & SACHSENHOFER, 1997). As expected, maceral composition was found to be highly predominated by the huminite group,



accounting for 80-97 % of the whole lignite's organic matter. This is normal for humic coals and lignites worldwide. The rest was composed of macerals of the liptinite and of the inertinite group. The latter two groups are essential as environmental indicators. Liptinite macerals such as sporinite, alginite, and liptodetrinite indicate relatively wet conditions of deposition under the relatively high water table level. In flowing waters these components may be concentrated and lead to the formation of liptobioliths, while in more calm waters sapropelic coals are formed. In Velenje, no such types of coal occur. Alginite was neither found microscopically nor by biomarker characterization (BECHTEL et al., 2003). Other liptinite macerals, e.g. resinite and/or suberinite, indicate the presence of resistant tree plants. Resinite points to coniferous flora and this was ascertained to be predominant over angiosperms both by palynological (ŠERCELJ, 1968, 1985/86; BRUCH – in HEMLEBBEN et al., 2000) as well as by biomarker studies. Inertinite macerals are indicators of dry conditions. They underwent the so called fusinitisation path of coalification (sensu DIESSEL, 1992). Besides pyrofusinite, which was formed by inhibited oxidation due to forest fires and was mostly blown from outside into the peat-formation area, some other inertinite, especially “semi”-inertinite macerals were formed within the peat, especially in the acrotelm part. Degradofusinitisation, the occurrence of textinite-B, observations such as increased reflectance around cell cavities indicate such oxidation processes. Funginite, sporadically as fungal attacks, also shows the presence of oxygen, because these organisms are active in aerated conditions. Bacterial activity, greatly responsible for the gelification process, was found out to be most probably of anaerobic nature (BECHTEL et al. 2003). However, aerobic bacteria might be more active in the lower part of the lignite seam, where, interestingly, the cellulose yield of wood is lower than in the upper part of the seam (BECHTEL et al., 2003), and the effects of gelification are less pronounced.

The highest portions of liptinite macerals, up to 13 % (*mmf basis*), occur in units I and II-b, whereas their normal content in other units does not exceed 8 %. Inertinite macerals were found to be the most abundant in units I and II-a. The fact that both maceral groups are most significant in the lowest, ash-richest unit I indicates that the peat-forming environment was a relatively high-energy one, i.e. fluvial and oxygen-rich. In such environment, mostly only well-rooted trees could grow and resist. In unit II-a, still in the forest environment, water table dropped a little and this caused somewhat drier conditions, with less mineral influx. Relatively dry conditions in units II-a, and II-b are, besides by true inertinites, also indicated by the somewhat increased presence of textinite-B.

Maceral data-base obtained by the quantitative micro-petrographic analysis of lignite in seam profile P-9k/92 was expressed by three facies significant petrographic indices (MARKIČ & SACHSENHOFER, 1997) (**Tab. 6.14**), known as the gelification index (GI), the tissue preservation index (TPI) and the groundwater influence index (GWI) (DIESSEL, 1986, 1992; CALDER et al., 1992).

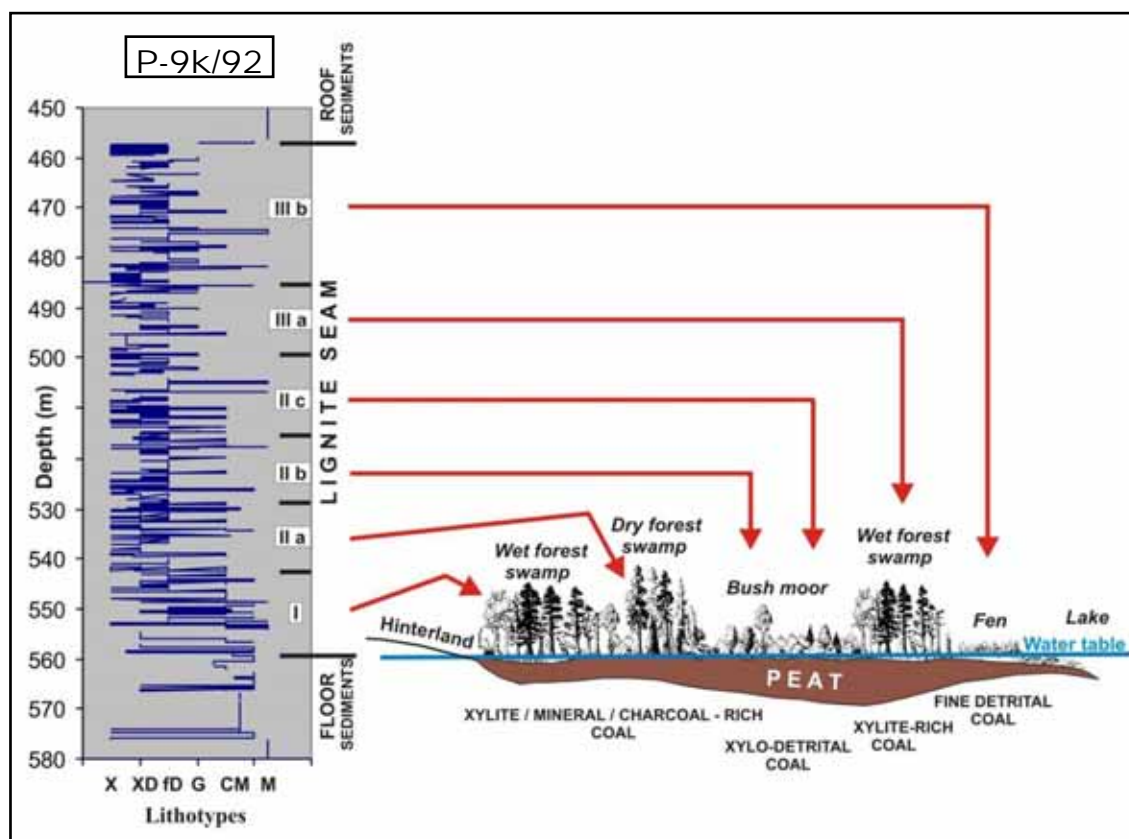
GWI contrasts by definition mineral-matter content plus corpohuminite versus huminite macerals (CALDER et al., 1991). Corpohuminite (also phlobaphinite) is a very subordinated maceral in comparison to other huminite macerals in the Velenje lignite. GWI thus reflects mostly the fluvial clastic input, from which the mineral matter content in the Velenje lignite mainly depends on. It can be thus concluded that GWI is a very similar palaeo-environmental indicator as is the mineral matter content (and the ash yield, respectively).

GI is a measure of gelification and thus reflects the intensity and nature of biochemical processes (DIESSEL, 1986, 1992). Indirectly, it reflects pH conditions, and to some extent,

supplementary to other indicators, also eH conditions. Gelification proceeds well in calm, waterlogged, eutrophic conditions, more intensively in alkaline than in acid environments. Both, aerobic, but to a greater extent anaerobic bacteria can enhance this biochemical process. When comparing the intensity of gelification, physicochemical resistance of original plant components must be taken into account because gelification proceeds faster and more intensively when affecting less resistant, lignin-poor or “soft” tissues than more resistant woody tissues rich in lignin, resins, waxes, suberins etc. Petrographic information about ratios between the two contrasted types of vegetal precursors is complemented by TPI (DIESSEL, 1986, 1992), contrasting telinitic, mostly tree-derived components versus detrital components of less resistant, mostly dwarf plants. Ratios between facies indices TPI and GI can be thus regarded as a complex tool for the interpretation of peat-forming environments and early diagenetic processes. In this study, the facies diagram after DIESSEL (1986) was applied.

Plotting of GI versus TPI values in the DIESSEL's diagram for separate units (**Fig. 6.61**) revealed a succession of the following peat-forming environments from the bottom toward the top of the lignite seam in the P-9k/92 profile: Unit I – wet forest swamp; Unit II-a – dry forest swamp; Units II-b,c – bush moor; Unit III-a – wet forest swamp; Unit III-b – fen (MARKIČ & SACHSENHOFER, 1997).

Several models of peat-forming environments are published in the literature. To illustrate the peat-forming environment as achieved by facies diagrams (**Fig. 6.61**), a well known model by TEICHMÜLLER, M. (1958, 1989) was applied also for the Velenje lignite as shown in **Figs. 6.62, 9.2 and 9.3**.



**Fig. 9.2:** Petrographic division of the lignite seam (P-9k/92 profile) into units I to III and interpretation of peat-forming environments referring to the classical model by TEICHMÜLLER, M. (1958, 1989) (modified from MARKIČ & SACHSENHOFER, 1997).

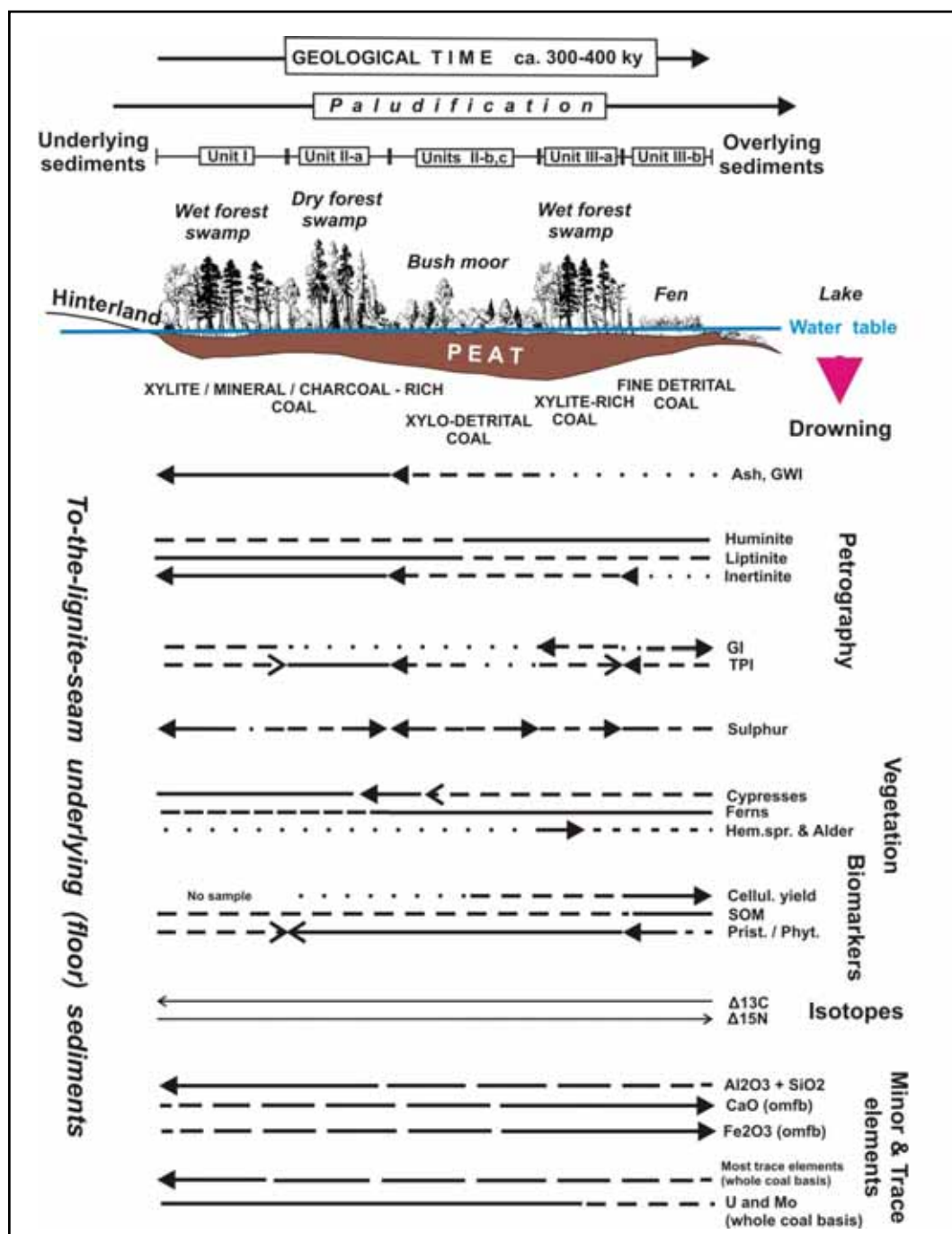
In the second studied borehole, P-8z/92, the peat-forming environment was wet forest swamp to fen. Since in the north peat accumulated closer to the Triassic carbonate rocks, the water was even more enriched in dissolved bicarbonate and hence the environment was still more alkaline, whereas the resulting lignite was more gelified and enriched in sulphur than the lignite in the central part of the basin.

In the above discussion, several aspects, indicators and processes of peat and lignite genesis have already been presented, and some additional will be debated in the continuation. To follow the discussion easier, the main lignite characterization parameters, their relative abundances and trends throughout the development of peat-forming environments and the resulting peat and lignite, respectively, are given in **Fig. 9.3**.

#### 9.4. Paleofloristic evidences and petrography-based interpretations

According to palynological studies of the Velenje lignite (ŠERCELJ, 1968, 1985/86; BRUCH – in HEMLEBEN et al., 2000), the lower part of the seam consists of the outstanding coniferous flora, such as *Taxodium* and *Sequoia*. As already mentioned, biomarker analysis by BECHTEL et al. (2003) confirmed this fact as well and also revealed that angiosperm woods were highly subordinated. Coniferous trees were highly resistant against still considerably strong fluvial influence, in which, at many places, smaller and worse rooted plants could not persist in larger areas. Paleofloristic study by BRUCH (in HEMLEBEN et al., 2000), which was carried out in the P-11r/98 borehole (**Fig. 6.24** – for situation see **Figs. 2.2, 2.4** and **6.2**), revealed three intervals of outstanding frequencies (forest swamps!) of the *Taxodium* and *Sequoia* cypresses in the lower part of the seam, approximately corresponding to the lower two petrographic units in the P-9k/92 profile interpreted as the wet and dry forest swamps, respectively (**Fig. 9.3**). The predominance of tree-dense vegetation and the relatively high energy of environment are reflected in variable TPI values (**Fig. 6.60**) and especially in the prevailing xylite-rich composition of lignite. Upward the seam, the density (frequency) of *Taxodium* and *Sequoia* conifers diminishes, although it still remains significant. What was replaced was replaced mainly by ferns (*Osmunda*) and to a much lesser but characteristic extent by angiosperms such as hemlock spruce, beech and alder. Ferns may correspond to the development of bush moor in units II-b and II-c as revealed by maceral analysis. But by biomarker analysis (BECHTEL et al., 2003), this type of flora, because of the lack of ferenes as typical biomarkers for ferns, was not undoubtedly confirmed to be very luxuriant. Non-lignin rich flora, as e.g. flora of ferns (and bushes) as interpreted from the palynological study, is reasonably reflected, especially in unit II-c, by one of the lowest TPI values in the whole profile. TPI increases and becomes more variable again - for the last time - in unit III-a, which is interpreted by the GI/TPI ratios as the wet forest swamp. Due to drowning and related water table rise, tree-dense flora was replaced by water-logged fen vegetation (herbs, dwarf bushes, reeds, sedges, only sporadic trees) (**Fig. 9.3**) characterized by high cellulose and low to negligible lignin yields. Such a lacustrine low-lying mire environment, as well as the type of vegetation, was largely favourable for biochemical processes of the early coal diagenesis, especially enhanced due to an alkaline character of the depositional environment.

Summarizing the previous discussion, a remarkable increase of gelification effects toward the top of the seam can be explained by more intensive bacterial activity in a relatively calm (no fluvial influence anymore), nutrient-rich, alkaline, and relatively reducing environment. The abundance of physically and chemically resistant coniferous woods dropped in the middle and



**Fig. 9.3:** Peat-forming environments and relative abundances and trends of the most indicative petrographic, palaeo-vegetal and geochemical (organic, inorganic and isotopic) parameters throughout the lignite seam as summarized from the following sources: petrography – MARKIĆ & SACHSENHOFER (1997); palaeo-vegetation – BRUCH (in HEMLEBEN et al., 2000), biomarkers – BECHTEL et al. (2003), isotopes – KANDUČ et al. (2005), minor and trace elements – MARKIĆ (2006). Solid lines (except for isotopes) mean relatively high contents (or values for petrographic indices and the pristane/phytane ratio), whereas dash and dotted lines mean moderate and small contents, respectively. Arrows mean increasing trends, either referring to contents or ratio values. For isotopes, arrows indicate an increase toward more positive values. Filled arrows mean pronounced trends; non-filled arrows mean slight trends. The sets of data are from different sites and objects, respectively – exact locations are reported in the papers cited above.

the upper part of the seam in comparison to its lower part. Coniferous woods were partly replaced by angiosperm arborescent woods and by bush and dwarf plants. Questionable is the

portion of ferns, because fern-derived pollen was recognized to be abundant (BRUCH – in HEMLEBEN et al., 2000), but on the other hand, ferenes as biomarkers of ferns have not been identified in the lignite (BECHTEL et al., 2003). Gelification was therefore also more effective because the source biomass material was less resistant, easily-to-be disintegrated into detritus and smaller xylitic pieces (xylo-detrite).

## 9.5. Coal rank evaluation of the Velenje lignite

Coal rank of the Velenje lignite was evaluated by using several parameters: huminite reflectance, moisture content, gross calorific value, volatile-matter and carbon contents (**Fig. 7.5**). Among these parameters, the gross calorific value at the bed-moist, ash free basis (*GCV<sub>bmaf</sub>*) is considered as the most significant coal rank indicator. Moisture contents of fresh samples were not determined. However, moisture contents of intact lignite samples used for geomechanical investigations (ca 35 % at the as-received basis) indicate that 45 % is a realistic bed moisture estimate for fine-detrital lignite. Taking this estimate into account, GCV values analyzed by laboratory calorimetry were re-calculated to *GCV<sub>bmaf</sub>*. The influence of mineral matter content on the lowering of the calorific value due to endothermic reactions was found to be significant. Therefore only lignite samples with ash yields below 12 % were considered for coal rank evaluation.

In low-ash samples from borehole P-9k/92, *GCV<sub>bmaf</sub>* is  $13.70 \pm 0.25$  MJ/kg (at 45 % bed moisture). If bed moisture of 40 or 50 % is considered, *GCV<sub>bmaf</sub>* is 15.25 and 12.23 MJ/kg, respectively. On the basis of these values, the Velenje lignite is classified as ortho-lignite (according to the ECE-UN, 1998 classification) or Weichbraunkohle (soft brown coal) (according to the “German” classification).

Whereas *GCV<sub>bmaf</sub>* clearly shows the ortho-lignite stage of the Velenje lignite, huminite reflectance (0.34 - 0.41 R<sub>m</sub> %) pretends a higher rank (meta-lignite to sub-bituminous stage; **Fig. 7.5**), underlining the observation that huminite reflectance is not a good rank parameter for low-rank coals. Minor differences also occur with carbon contents. Such discrepancies are not unknown in coal rank estimations (e.g. CORRÊA DA SILVA, 1989) and originate mainly from coal matrix heterogeneity, differences of measured target objects, as well as from measuring methods themselves.

Concerning the petrographic components of lignite, GCV and carbon contents of xylite (“fossil wood”) pretend a markedly lower rank than fine-detrital lignite, of which especially the gelified variety seems representative for rank evaluation (**Fig. 7.5**). These differences reflect the different composition of the source material and the different pathways and intensities of early diagenesis. Variations of the *GCV<sub>bmaf</sub>* values throughout the seam profile (**Fig. 7.7**), therefore, do not reflect differences in rank, but different petrographic compositions (xylite versus fine detritus versus mineral matter ratios).

Similar is true for the huminite reflectance, which, even though measured on a single maceral variety (eu-ulminite), showed considerable variability throughout the lignite seam profile (**Fig. 7.4**). In this case, huminite reflectance variability was attributed to optical effects, such as suppressed huminite reflectance due to lipoid substances or increased reflectance due to incipient (semi-)fusinitization.

## 9.6. Relationships between petrographic, organic geochemical, inorganic geochemical and isotopic parameters, and related interpretation of the lignite's genesis

A very interesting support to understand the conditions and processes of the early peat and lignite genesis was achieved by studying biomarkers and isotopy of organic carbon in 31 lignite samples and eight fossil wood (xylite) fragments from borehole P-9k/92 (BECHTEL et al., 2003). In addition, the carbon isotope composition of cellulose extracted from the wood fragments has been investigated. Important additional results have been gained from the comparison of geochemical results and petrography-based facies indicators (tissue preservation index – TPI, and gelification index – GI; see **Chaps. 6.4.1.4.2 and 6.4.1.4.4**). Some outstanding results of these complementary investigations are summarized below:

- Based on the molecular composition of terpenoid biomarkers, all wood fragments are identified as derived from gymnosperms. Terpenoid biomarkers also indicate a predominance of gymnosperms over angiosperms in the lignite samples, which is consistent with palynomorphic spectra dominated by pollen of the *Sequoia-Taxodium-Metasequoia* plant community rather than by angiosperms. Evidence is also provided that the preservation of plant tissue (TPI) is controlled by the input of resin-rich, decay-resistant conifers.
- Sections of the seam characterized by a high degree of gelification (GI) show high contents of hop-17(21)-ene but low hopane concentrations. The results suggest that the gelification of plant tissue may be governed by the activity of anaerobic rather than aerobic bacteria.
- Cellulose yield was found to increase in the fossil wood samples upward the seam profile (**Fig. 9.3**) from 10.6 % in sample 42 (unit II-a) to 35.8 % in sample 95 (unit III-b). This observation together with petrographic and geochemical data of gelified and ungelified fossil wood provides evidence that aerobic microorganisms are responsible for decreasing cellulose contents, whereas anaerobic bacteria control the degree of gelification.
- A positive correlation was found between gelification (GI) and the soluble organic matter (SOM). The latter reflects the presence of free lipids of microbial origin and/or the presence of plant polymers derived from biogeochemical degradation. The positive correlation between SOM and GI can be to some degree the reason for a somewhat higher portion of texto-ulminite A (dark, hydrogen rich variety of texto-ulminite, exhibiting suppressed vitrinite reflectance) in the upper part of the seam, particularly in unit III-a (**Tab. 6.14**).
- The SOM yield typically varies between 12 and 30 mg/g Corg. Samples with high SOM yields (> 25 mg/g Corg.) are listed in **Tab. 9.1**. With the exception of samples 33 and 45, all samples with high SOM yields belong to unit III. The highest SOM yield (~39 mg/g Corg.) was extracted from sample 72. This sample is strongly gelified (GI = 3.50), and very rich in organic-bound Ca (CaO = 34.4 % domf). Similar relations are true for most lignite samples with high SOM yields (**Tab. 9.1**) emphasizing the relation between an alkaline lake environment (high CaO contents!),



enhanced bacterial activity, resulting advanced gelification, and the formation of soluble hydrocarbons, NSO compounds and asphaltenes as “by products” of the biogeochemical degradation.

- Pristane/phytane ratios decrease upward in the Velenje lignite seam. Since low pristane/phytane ratios indicate anaerobic conditions (DIDYK et al., 2003), this result suggests gradually more reducing environments during peat/lignite accumulation.

**Tab. 9.1:** Ash yields, gelification indices (GI), and CaO contents in the samples (P-9k/92borehole) from which more than 25 mg of SOM per g of  $C_{org.}$  was extracted. Data are compiled from MARKIČ & SACHSENHOFER (1997) for ash and GI, from BECHTEL et al. (2003) for SOM; and from MARKIČ (2006) for CaO. For a comparison, normal ash yields of the lignite are above 15 %, GI is normally below 2, CaO (domf) contents are mostly below 10 % except for unit III, where they are higher, and SOM yields are mostly below 25 mg/g $C_{org.}$ . Abbreviations: wt. % - weight %; domf – dry, organic matter free basis;  $C_{org.}$  – organic carbon.

Smp.	Ash (wt.%,db)	GI	CaO (wt%,domf)	SOM (mg/g $C_{org.}$ )
92	8	3.43	29.3	n.a.
91	13	2.79	15.7	30.0
90	7	<b>7.36</b>	31.2	n.a.
85	16	2.50	n.a.	30.3
82	13	1.84	16.0	26.2
73	8	1.94	29.9	n.a.
72	9	3.50	<b>34.4</b>	<b>38.7</b>
68	9	2.21	28.7	27.2
45	14	1.32	n.a	27.3
33	44	0.81	n.a	26.3

Interesting results regarding relationships between the intensity of gelification and the intensity of mineralization on one side and the isotopic composition of carbon and nitrogen on the other side were achieved by the isotopic study of these two elements in samples of different lithotypes taken vertically and laterally from throughout the lignite seam as accessible in the underground mine workings (KANDUČ et al., 2005) (**Chap. 6.3.1.7, Fig. 6.16**). The lithotypes involved into the study were poorly, moderately and strongly gelified detrital lignite, xylite (fossil wood), and semifusitic and fusitic lignite. The study revealed the following results and aspects:

- Bacterially governed process of gelification causes isotopic fractionation of carbon ( $\delta^{13}C$ ), whereas mineralization process causes isotopic fractionation of nitrogen ( $\delta^{15}N$ ) (**Fig. 6.16-a**). The latter process is a tight reflection of oxidation, which causes the loss of organic matter and relative enrichment in inorganic residual matter, as well as formation of inertinitic components. Indeed, semifusitic and fusitic samples show some of the most positive  $\delta^{15}N$  values, which are characteristic for mineralised organic matter, whereas strongly gelified samples are characterized by the least positive values of this isotope.
- The  $\delta^{13}C$  values are more discriminating than the  $\delta^{15}N$  values. The most negative  $\delta^{13}C$  values (-28.7 to -27.2 ‰) are characteristic for strongly gelified detrital lignite,

whereas a wide range from -27.5 to -23.0 ‰ is characteristic for xylites (KANDUČ et al., 2005). A similar relation, i.e. depletion of  $^{13}\text{C}$  in “whole” lignite in comparison to xylite and from-wood extracted cellulose was also ascertained by PEZDIČ et al. (1998) and BECHTEL et al. (2003) (**Fig. 6.17**). For an overview of carbon isotopic and biomarker variation of a range of coals and fossil woods in the Central Europe the reader is referred to BECHTEL et al. (2008).

- Decrease in  $\delta^{13}\text{C}$  values from xylites toward detrital and strongly gelified detrital lignite (BECHTEL et al. 2003; KANDUČ et al., 2005) is interpreted by the bacterial activity which is well known to affect fine detrital organic matter more easily than resistant xylite pieces (e.g. DIESSEL, 1992 – his Fig. 3.4), and/or by the considerable presence of isotopically light organic matter from leafs, resins and bark in fine detrital coal matrix (sensu HÁMOR-VIDÓ & HERTELENDI, 1996).
- Bacterial activity as a key factor of the biochemical gelification process leading into enrichment in the light carbon isotope composition is dependent on the alkalinity and the redox potential of the depositional environment. It is enhanced in more alkaline environments. In the case of the Velenje lignite it was postulated that gelification was governed especially by anaerobic bacteria (BECHTEL et al., 2003), whereas considerable alkalinity is ascertained by sulphur (Stot, *dry basis*) contents of 2 to 3 wt. % (MARKIČ & SACHSENHOFER, 1997) and considerable CaO (up to 30-35 wt. %) and MgO (up to 13 wt. %) contents in inorganic matter of low-ash lignite varieties (**Tab. 8.6** and **Fig. 8.1**).
- As seen from **Figs. 6.16** and **6.17**, samples of strongly gelified detrital lignite are characterized by a narrow range of carbon and nitrogen isotope compositions (KANDUČ et al. 2005). This indicates uniform effects of both the gelification and the mineralization processes and can be explained in a way that original organic material was homogeneous and was transformed in unique eH reducing environment(s).
- A wide range of carbon and nitrogen isotope compositions for xylites as analyzed by KANDUČ et al. (2005) points out that xylites were transformed in a wider spectrum of environmental conditions, and/or that xylites belong not only to gymnosperms but also to angiosperms. Namely, after BECHTEL et al. (2008) angiosperm woods can have similar carbon isotopic composition as (matrix) coals.
- Because carbon and nitrogen isotope composition is not depth- (time-) dependant but almost exclusively lithotype dependent it can be supposed that the processes of humification, gelification and mineralization were temporally and spatially very similar and uniformly intensive throughout the peat and the lignite formation.

## 9.7. Minor and trace element geochemistry of the Velenje lignite

The composition of inorganic matter in lignite was analyzed on whole coal samples in the P-9k/92 lignite seam profile. Contents of (coal)minor elements were expressed in the form of oxides at the dry, organic matter free basis (*domf*), whereas trace elements at the dry, whole coal basis (*db*). Main results of the geochemical study and some additional explanations are given below:

- Inorganic matter of the Velenje lignite in the studied samples is characterized by SiO<sub>2</sub> (20–52 %), Al<sub>2</sub>O<sub>3</sub> (15–29 %), Fe<sub>2</sub>O<sub>3</sub> (6–24 %), and CaO (2–34 %) components (**Tab. 8.6**).
- Contents of the (coal)minor element oxides significantly depend on the inorganic matter yield. In the range of the ash yield (estimated as difference between 100 % and LOI %) between ca. 5 % and 20–25 %, SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> content increases from 40 to 80 % with increasing ash yield, whereas above this threshold it is constant (**Fig. 8.1 – graph 2**).
- On the contrary, CaO, MgO, and Fe<sub>2</sub>O<sub>3</sub> contents decrease with increasing mineral matter content below the mentioned 20–25 % ash threshold (**Fig. 8.1 – graphs 5-9**). Taking into account that inorganic carbon contents are low, it is concluded that Ca, Mg, and possibly also Fe are mostly organically bound.
- Upward the seam profile (**Fig. 8.3**), the sum of SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub> continuously decreases, whereas Fe<sub>2</sub>O<sub>3</sub> and CaO slightly increase.
- Since SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> are closely correlated ( $r^2 = 0.92$ ), and other minor elements are negligible, kaolinite is presumed as the main clayey (argillitic) mineral in the lignite. Kaolinite is a frequent clay mineral in coals (e.g. discussion by WARD, 2002) because of rather intensive leaching processes in peat forming environments, in which the composition of the mineral matter is considerably influenced by humic acids. However, in view of the alkaline peat-forming environment, which prevailed in the Velenje case, a detrital origin of kaolinite is also suspected.
- Fe<sub>2</sub>O<sub>3</sub> contents are especially high in samples 34, 37 and 40 from the lower part of the seam (**Fig. 8.1 – graph 5** and **Fig. 8.3**). All of them are also rich in inorganic carbon, thus indicating the presence of siderite, which was additionally proved by SEM and EDS techniques (**Fig. 8.8**). Siderite indicates moderate eH conditions (more oxygen-rich than if pyrite is present). This fact is consistent with supposed higher aeroby in the lower part of the seam than in its upper part.
- The upward increase in CaO content in the lignite seam profile (**Fig. 8.3**) agrees with the increase of gelification degree (GI) (**Fig. 6.60**). As already discussed, GI and CaO are positively correlated with soluble organic matter (SOM) (**Tab. 9.1**) and negatively with the pristane/phytane ratio, which is a measure of the redox potential. From these findings it is concluded that gelification of organic matter in the upper part of the seam was enhanced by alkaline peat-water, and governed predominantly by anaerobic bacteria.
- XRD investigations revealed that “moderate”-temperature (ca. 400°C) ashes are an adequate material for mineralogical investigations. Whole coals yield too amorphous XRD spectra.
- In our case, whole coal samples were found as an acceptable analytical material for trace-element geochemistry (**Tab. 8.9**). A great majority of trace-elements analyzed in whole lignite samples was above detection limits.

- Trace-element contents of the Velenje lignite are within normal limits in comparison to the coals throughout the world (**Tab. 8.9** and references there-in). Exceptions are U and Mo.
- Contents of U (5–15 ppm) and Mo (5–20 ppm) are both higher in comparison to world coals. Compared to the underlying and overlying strata, the contents of these two elements are not reduced within the lignite seam as it is true for almost all other elements, which are therefore considered as inorganically bound in minerals. U and Mo in the Velenje lignite are independent from the mineral matter yield and are therefore presumed to be organically bound. Their contents (**Tab. 8.9**) do not vary considerably along the seam profile (**Fig. 9.3**). U is known to be immobile in reducing environments. The latter are caused i.a. by bacterial activity, which is enhanced by alkalinity. Therefore, U contents can be significantly enriched in the so called Ca-rich coals.
- Apart from U and Mo, at least partial organic bonding can be presumed for Ba and Sr. According to investigations of ŠLEJKOVEC & KANDUČ (2005), also As was found to be organically bound. Because our results (**Tab. 8.9**) do not confirm this fact unambiguously – even more – increasing total As content with increasing mineral matter content shows preferential inorganic bonding – we presume that As can be bound both inorganically (preferentially) and organically.

## 10. EPILOGUE

More than 15-years of petrological studies of the Velenje lignite showed that different, one another supplementing methods of investigations enable to obtain reliable results referring to a complex interpretation of the studied lignite – from interpreting original peat-forming environments, through understanding the relevant processes of peat/lignite diagenesis, to the description of the structure and technological properties of this lignite as we can observe, exploit, and use now.

One of the fundamental approaches was to study the lignite in the broadest spectrum of spatial (and temporal) dimensions, from meter to centimetre scales in the case of petrological mapping of lignite in the underground mine workings and borehole cores, to micrometer scales in the case of optical microscopy. In this way, macro- and micro-facies variability of the lignite was ascertained. In the frame of the coal macro-facies study of the Velenje lignite, a specific lithotype classification was established (MARKIČ et al., 2001).

A systematic micro-petrographical analysis of the lignite seam was done in the core profiles of the boreholes P-9k/92 (central part of the basin) and P-8z/92 (northern margin of the basin). This analysis was carried out in a strictly quantitative way. For the first time in the studies of coals in Slovenia, interpretation of peat-forming environments throughout a seam profile was carried out using petrographic indices (GI, TPI, and GWI) and facies diagrams after DIESSEL (1986, 1992) (MARKIČ & SACHSENHOFER, 1997).

Recently, scanning electron microscopy (SEM, low vacuum) was applied in the study of separate lignite samples, also for the first time in coal studies in Slovenia. Besides general advantages of the SEM microscopy (large magnifications, 3-D imaging, simple sample preparation) it was found out that especially elemental composition of inorganic inclusions, effects of mineralization (together with possibility of mapping chemical elements), porosity, cleat-and-fracture system, and sub-(optical) microscopical texture can be successfully studied by this technique.

The present state of knowledge of the petrology and genesis of the Velenje lignite benefited enormously from a range of complementary studies, which involved palynology (BRUCH – in HEMLEBEN et al., 2000), biomarker analysis (BECHTEL et al., 2003), carbon and nitrogen isotopic analysis (KANDUČ et al., 2005) and minor- and trace-elemental geochemical analysis (MARKIČ, 2006). Unfortunately, a continuous analysis of the main-elemental composition (C, H, O, N, S) was not performed although the analytical samples were prepared. Somewhat greater role should be dedicated in the future to the XRD mineralogical investigations, involving not only the lignite seam but also the underlying and overlying sediments.

Causal relationships between different compositional, textural and structural elements as obtained from the above cited studies and petrography, which reflect processes of peat/lignite genesis, are in general well explanatory one another. In spite of that, of course, new campaigns of detailed and well organized petrological investigations (in the broadest sense) would still increase the present level and accuracy of this type knowledge.

In the praxis of the Velenje Lignite Mine, petrological investigations of lignite gained quite an important role in applied studies such as studies of gas dynamics and rock-mechanics. It has been realized that gas and rock-mechanical properties are considerably dependant on the petrological properties of coal. Predicting composition, texture and structure of the lignite in front of the mine workings is one of the main activities in this framework, in recent times also in close teamwork with different geophysical and petrophysical investigations and measurements. Macro-petrographic procedures for describing and mapping of lignite are now fully implemented and routinely used in the Velenje Lignite Mine. Applied investigations are important for direct solving of different practical problems. However, fundamental understanding and knowledge about the petrology of coal is not only very helpful, but in many cases inevitable to answer different questions coming from the mining praxis and other branches of lignite investigations.



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