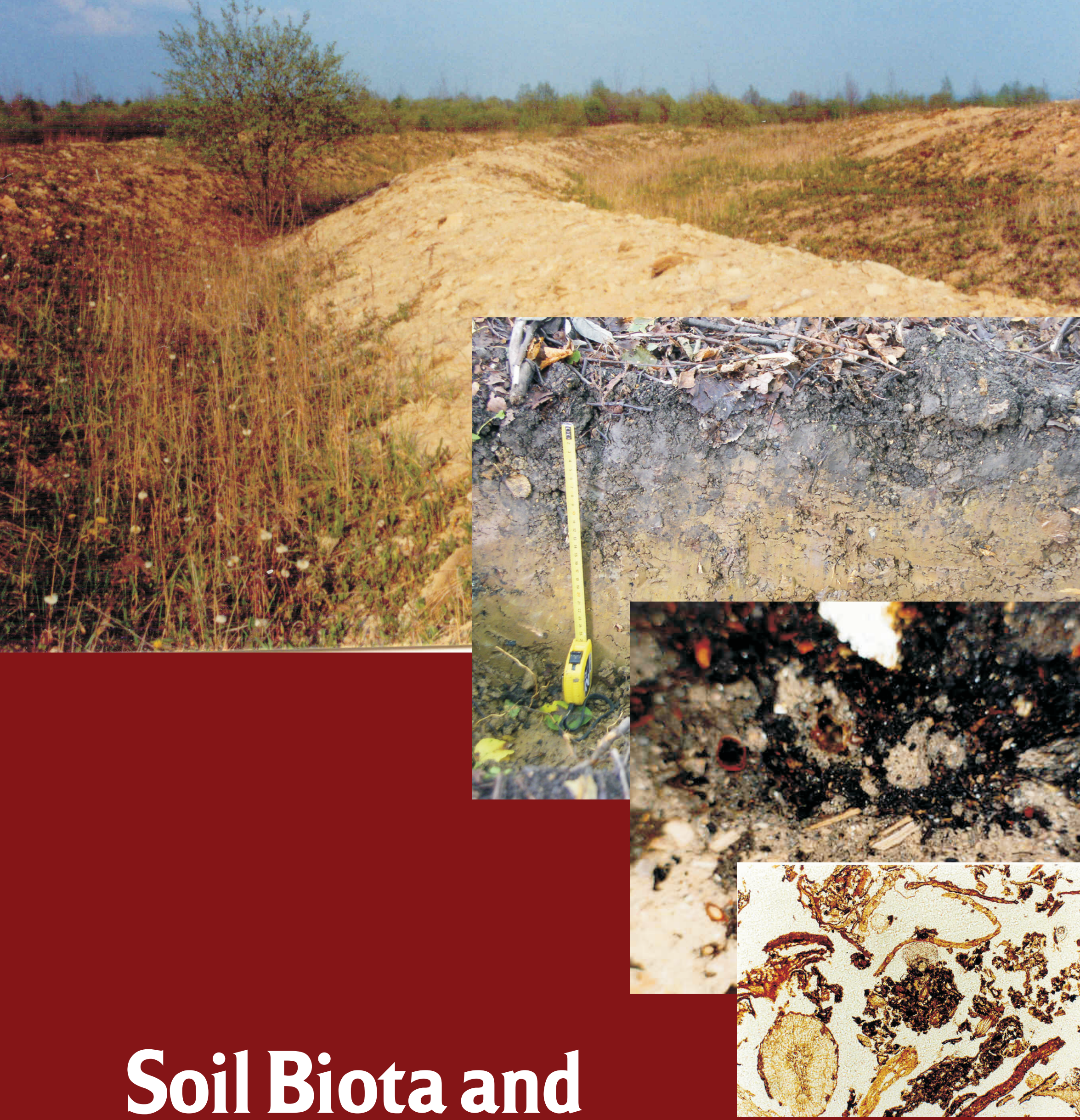

Soil Biota and Ecosystem Development in Post Mining Sites

Editor

Jan Frouz

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Preface

Mining supplies numerous raw minerals that are essential for economic development. In many cases, however, mineral extraction causes severe destruction of the environment. Large areas can be literally erased by excavation and dumping of overburden. In addition, mining and post-processing of raw materials may accelerate weathering processes and chemically alter the environment through, for example, acidification or pollution by heavy metals.

Environmental damage brings the necessity for ecosystem reconstruction in affected areas. Numerous approaches to land reclamation have been developed. Natural processes collectively referred to as ecological succession, however, bring about gradual ecosystem development without the assistance of man. These processes may be relatively slow, particularly in their early stages, but there are many examples of how they have lead to the development of functional ecosystems in the long-term, typically after several decades. In this book, we pay attention to the study of these successional processes. Firstly, only comparisons between the results of reclamation technologies and those of natural succession at unreclaimed sites of the same age can provide us with real information about the added value of reclamation. Secondly, a better understanding of natural succession processes may inspire numerous future improvements to restoration technologies. Finally, post-mining sites represent an excellent model for studying succession processes and may substantially improve our knowledge about these ecological phenomena.

Beside the large practical value of biological studies at post mining sites, their fundamental contribution to our knowledge in many fields of ecology is still underestimated. There are many reasons why post-mining sites represent suitable study sites for unraveling successional processes. Mining creates newly disturbed patches on similar substrates using a similar technology over a long time period. Crucially, the time when these sites are established is usually recorded. This makes post-mining sites an outstanding subject of chronosequence studies. Mining disturbances are often very extensive, which allows us to study succession processes on the landscape scale. Mining operations are similar in different countries, allowing comparisons of succession processes over vast climatic gradients.

Post-mining sites are areas of freshly exposed geological substrate resembling the consequences of a large geological event such as a landslide or glacier movement. Moreover, ecosystem development is considerably fast in many cases, providing data over a manageable time frame. Post-mining sites represent a very dynamic landscape whose terrain has been modified often on a very large scale. Post-mining sites are therefore excellent places for carrying out manipulation experiments that would be logistically and in some cases ethically problematic in other places.

Soil recovery is a basic precondition for reconstruction of a functional ecosystem at post-mining sites because soil provides many essentials ecosystem services. The climate and geological substrate play the principal role in soil formation across large areas. Locally, however, also other factors such as the biota become important. Plants provide organic matter that feeds the detritus food web in the soil and facilitate accumulation of soil organic matter, which affects many soil properties. In addition, plants affect substrate weathering, aggregate formation, water infiltration and many other soil properties. Plants and soil organisms play a crucial role in soil formation. Soil organisms may affect plant fitness by numerous interactions with roots, such as mycorrhiza, symbiotic nitrogen fixation, root herbivory and other activities of various beneficial or pathogenous microorganisms in the rhizosphere. Other important functions of the soil biota are litter decomposition and nutrient release, structure formation, mixing of the soil profile, and many other processes affecting soil formation and nutrient cycling, which, again, indirectly affect soil formation. The role of soil organisms in soil formation at post-mining sites is only partly understood. Plants are studied more intensively in the context of post-mining sites, but their belowground parts are also underexplored, as are above-belowground interactions. The aims of this book are to summarize our knowledge about the role of the soil biota in soil formation at post mining sites, to present a synthesis, and to offer an outlook for future research and point out practical some implications. We focused mainly on open-cast coal mining because this kind of mining is widespread, causes large-scale disturbances and because this type of mining provides a large portion of the available information on the role of soil biology at post mining sites.

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Acknowledgement

When I decided to summarize the current state of knowledge in this field in a book I did not realize what a complex task this will be. Herein I would like to place on record my appreciation of the help I received from several persons in the course of preparation of this book. First of all I would like to thank authors of all the chapters. Martina Frouz Vokounová is thanked for her work on graphics, Fred Rooks, Peter Lemkin and San Francisco edit are thanked for linguistic improvements of the text. I thank my family for bearing up with my pre-occupation with this book project. Finally I would like to thank the Czech Science Foundation for sanctioning a grant (No. P504/12/1288) without which it would not have been possible to prepare this manuscript.

Jan Frouz
Prague

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CHAPTER 1

Geological Substrates and Heaping Process of Coal Mining Operations in the Sokolov Basin, Czech Republic

Implications for Reclamation and Soil Development

Petr Rojík

Introduction

Sedimentary deposits in the Czech Republic currently provide a significant proportion of global coal and industrial minerals extraction. The resources extracted specifically include kaolin (10.3% of world production), brown coal (4.2%), feldspar (2.0%), diatomite (1.8%), quartz sands (1.3%), bentonite (1.4%), and ceramic clays (Starý et al. 2011).

Coal is a major component of the Czech Republic's energy portfolio. National and economic interests favor surface mining given appropriate economical conditions due to its greater potential extraction rates. These may reach 95% for a given coal deposit and greatly exceed the underground extraction rates, which typically can access no more than around 40% of the material. Large opencast mines for brown coal are situated in the NW part of the country in the Most and Sokolov Basins. Underground mining

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for bituminous coal occurs mostly in the NE part of the country around the cities of Ostrava and Karviná in the Upper Silesian Basin. Coal mining operations have affected the landscape for centuries, causing extensive environmental damage (Fig. 1).

This contribution describes the Sokolov coal mining district as a case study of geological properties and processes in spoil deposits as they pertain to reclamation and reestablishment of natural ecosystems.

Fig. 1 Aerial view of the Jiří open pit mine and the Jiří spoil deposit near Sokolov. Photograph taken by J. Klimaj in 2010.

The Sokolov Basin—Geological Setting

The Sokolov Basin is situated in the NW part of the Czech Republic and constitutes part of the Bohemian Massif. Along its axis, the basin extends 36 km in length and 9 km in width in a SW-NE direction, occupying a 312 km^2 area. The Tertiary period hosted an ideal climate and also provided the geological conditions necessary for coal preservation (Burdigalian optimum). The subsidence of the basin facilitated rapid coalification and preservation of the coal seams (Rojík et al. in Pešek ed 2012). The tectonic collapse of the Sokolov Basin occurred within a dilatational strain field. A series of radial faults reflect the extensional pattern imparted by the deforming lithosphere. The dilatational stresses caused individual tectonic blocks to subside, becoming depositional basins often flooded as swamps and lakes. The major extensional faults also extended into the Earth's mantle giving rise to an alkaline basaltic igneous suite.

The extensional event lasted only about 2.7 million years. Fossil evidence indicates that the most intensive deformation began in the Oligocene (Rupelian) and ended by the Miocene (Burdigalian) period. Paleomagnetic data also indicates intensive deformation beginning in the Oligocene (24.0 Ma) and lasting until the Miocene (21.3 Ma; Rojík 2004, Rojík et al. 2012).

The continental volcano-sedimentary succession of the Sokolov Basin reaches thicknesses of 360 m. It consists of about 55% volcanic rocks, around 30% sediments derived from disintegrated kaolin weathering crusts, and around 15% organic sediments (Fig. 2). The lithostratigraphic scale for the Sokolov Basin is temporally constrained by means of both biostratigraphic and magnetostratigraphic data (Rojík 2004). The Tertiary succession can be subdivided into four formations separated by disconformities (Fig. 2). The Staré Sedlo Formation (Eocene, ca. 35 Ma in age) represents the initial stage of basin development. The Nové Sedlo Formation (Oligocene, ca. 24–23 Ma in age) and the Sokolov Formation (Miocene, ca. 23–22 Ma) represent the main stages of extension, tectonic subsidence and volcanism. These formed in environments characterized by igneous activity and gravity flows that merge into alluvial fans, lakes and swamp environments conducive to peat and coal formation. The Cypris Formation (Miocene, ca. 21–20 Ma in age) deposited in intermittent meromictic lakes and marks the cessation of endogenic processes.

Post-mining Landscape and Associated Geological Processes in the Sokolov Basin

The historical development of coal mining in the Sokolov Basin is similar to that observed throughout the Czech Republic. Prior to the large-scale mining operations that began in the second half of the 19th century, the Sokolov Basin hosted a balance of agriculture and natural ecosystems that included 36% fields, 35% forests, 19% meadows, 6% grazing land and numerous ponds (Fig. 3). Recultivation of the Most area began in 1908 and in 1910 for the Sokolov district (Beran 2000). Systematic large-scale recultivation has continued since 1953 (Dimitrovský 2001) but preferred land use objectives have changed since that time. During its early decades, agricultural recultivation emphasized original land use practices. Subsequent forest restoration of upland and lakes of residual pits were considered most beneficial. The principles, methods and objectives of ecological restoration are currently subject to debate and revision. Reclamation based on spontaneous or controlled succession and associated

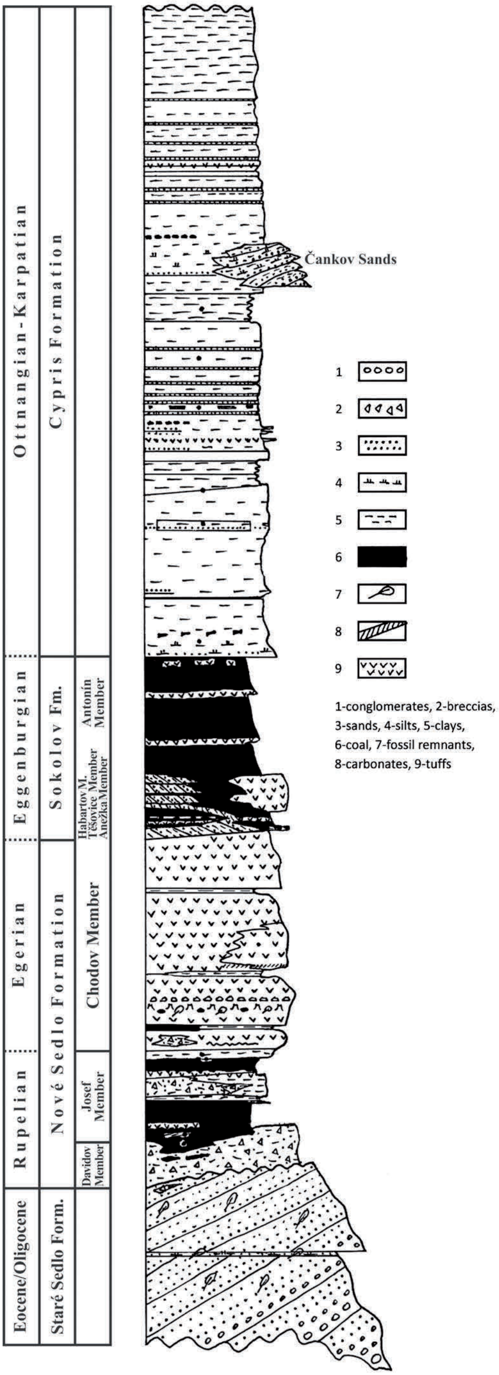

Fig. 2 Tertiary stratigraphic column for the Sokolov Basin (based on Rojík 2004).

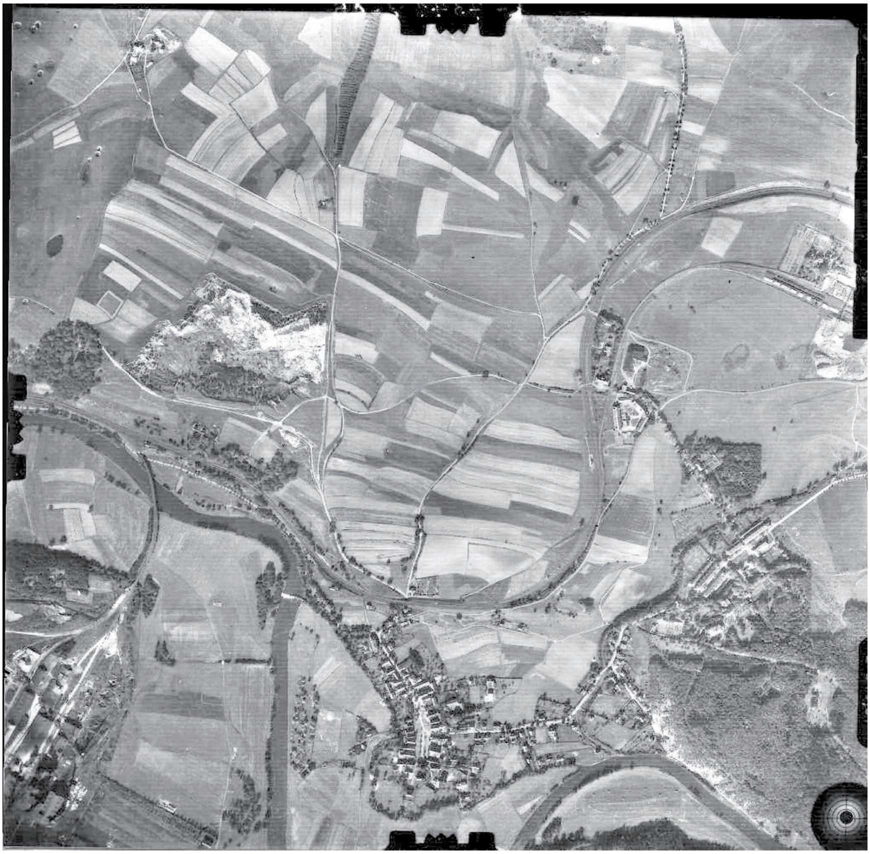

Fig. 3 Agricultural landscape pre-dating opencast mining operations in the Sokolov Basin in 1947, P. Rojík archive 1947.

methods (e.g., renaturalization) have helped diversify the landscape and land use. This practice establishes test areas and protected zones in order to support maximal geodiversity and biodiversity, and protects cultural landmarks connected with the pre-mining activities and mining heritage.

In the Sokolov Basin, bucket-wheel excavators operating in the opencast mines transport coal from the 30 to 45 m thick seam along a conveyor belt system to uploading stations for further transport to processing plants and freight systems. The overburden usually ranges in thickness from 80 to 120 m and is stripped by means of bucket-wheel excavators or (less often) by mechanical shovels. The material is then transported to restoration spoil dumps by conveyor belts or freight train. The dumps have become significant landforms that span tens to thousands of ha in area and reach more than 100 m in altitude. The operation has established spoil deposit sites inside the exhausted areas of the coal pits as well as outside the mining area.

The area of the basin most affected by intensive surface and underground coal mining and processing from past to recent times spans a 115 km^2. The nine largest outer dumps cover a 49 km^2 area, or 43% of the total mining area. The overburden transferred from the pits to the inner and outer dumps occupies a volume of 1.8 billion m^3. The average thickness of deposits that make up the outer dumps is 32 m. The average rates of overburden denudation ("artificial erosion") and of remobilization/redeposition of spoil debris ("artificial sedimentation") exceed the natural rates of these processes as they occurred during the Tertiary in the Sokolov Basin by four orders of magnitude.

The mining operation as a whole has caused dramatic changes in the area's geomorphology relative to the original relief of the Sokolov Basin (Fig. 1). The post-mining landforms consist of various depressions in opencast mines and topographic relief in outer dumps surrounding the mine site. The surface mine sites and overburden heaps often follow and conform to pre-existing landforms. The opencast mines for example excavated down-dropped tectonic blocks that formed topographic depressions. During initial pit development, the excess overburden material required the establishment of the dump site outside of the coal-bearing area. The spoil dumps were thus situated along the basin's uplifted shoulders, which exhibit positive relief exaggerated by spoil deposition. During and after excavation, the pits are continuously filled with overburden material which does not typically surpass the original ground surface level due to the rheology of the unconsolidated debris and instability of the slopes surrounding the pit. The residual pits often flood and thus further exaggerate the original landscape morphology.

The flooded residual pits are surrounded by outer dumps that exceed the basin's original topographic relief. Mining operations have created a distinct topographic constrast between the pit bottom and its surroundings of 100–250 m, which greatly exceeds the original 10 to 40 m of relief. The post-mining geomorphology of the site has also become more rugged and discontinuous relative to the pre-mining landscape. The human-made landforms are separated by tectonic faults and built around coal seam outcrops. The fault scarps and surfaces that border the spoil dumps are steepened and vulnerable to land slide. The boundary areas between dumps and pits also serve as a corridor for communication routes and provide a location for industrial and service operations.

Processes Inside the Spoil Heaps

The typical mine spoil deposit can be described according to the petrographic classification system of Konta (1972) as a block aggregate composed of claystone debris and loamy (silt > clay > sand size) groundmass. The deposit exhibits unsorted clast-size distributions and tabular morphologies among its claystone debris. Layer thickness corresponds to the relief of nearby landfill features and diagonal bedding patterns reflect the angle of repose of particular rocks. Certain beds show sharp, well-defined boundaries while other areas of the deposit exhibit heterogeneities and other artefacts of mining and stowing activities.

The spoil heaps consist of unconsolidated material that behaves as a highly permeable substrate. Groundwater infiltration causes secondary vertical differentiation of three subhorizontal zones within the heaps.

The upper unsaturated horizon of the spoil deposit is rusty brown and occupies the vadose zone (oxic environment). Layers from the unsaturated zone include claystone aggregates with well-preserved structure within a fine loamy matrix. The claystone debris consists of indurated, angular clasts, covered by thin coatings of Fe and Mn-hydroxides. The lower zone of the spoil deposit includes blue-grey to green-grey sediments formed within the anoxic phreatic zone. Secondary alteration has obscured original clast morphology and sedimentary fabrics. The sedimentary groundmass has a soft to pasty consistency and consists of aleuropelite transformed from the original aggregate material. At the very base of the spoil deposit, landfill material intermingles with autochthonous soils. A narrow transitional horizon between the upper and lower zones reflects variation in the groundwater level and alternating oxic and anoxic conditions. Signs of water level shifts correlate with the timing of local precipitation, given the expected delay of several hours to two days. The middle transitional zone consists of thinly laminated sedimentary horizons showing alternating characteristics of both the upper and lower zones.

The spatial distribution and thickness of each zone vary with topographic relief, morphology of the foundation and the presence or absence of a well-functional drainage system. These factors in turn result from the shape, compaction and levelling of the spoil deposit.

The rock debris in the spoil deposit experiences biochemical weathering, including hydrolysis, hydration, dissolution, re-precipitation and redox reactions. Physical weathering processes such as differential compaction, differential decomposition of the rock particles depending on their position relative to the ground water level, changes in rheology and mass wasting also affect the debris.

Precipitation of Secondary Minerals Associated with Acid Drainage from Spoil Heaps and Open Pits

A wide range of aqueous environments have developed in association with mine drainage in the Sokolov Basin. A specific assemblage of secondary minerals develops in rills which concentrate acid mine drainage from pyrite, marcasite and greigite weathering. The precipitates differ in color and mineralogical composition depending on pH and concentration of sulfate and ferric ions in the drainage effluent. Jarosite occurs under the most acid conditions (pH 2.3 to 3.0). Schwertmannite precipitates from solutions having pH values of 3–4 and occassionally from less acidic conditions. Ferrihydrite has been observed in association with solutions having pH values of 5 and above. Lepidocrocite develops under neutral to slightly alkaline aqueous conditions (pH 7–9). Goethite (FeO(OH)) precipitates throughout the effluent pH range, but always in association with other minerals (Murad and Rojík 2005). Jarosite-goethite bearing cherts with concentric fabrics precipitate in acid drainage solutions occuring within the former Georg pit (Fig. 5). In addition to mobilizing anions and heavy metals, acid mine drainage also serves to hydrolize carbonates, feldspars and clay minerals.

Erosion and Redeposition Processes

The abandoned open pit referred to as the Silvestr mine (Fig. 6) offers a useful example of sedimentary reworking as it occurs in the Sokolov Basin. Silvestr mining operations ceased in 1981. In place of a traditional reclamation effort, the residual pit is gradually being filled with coal combustion residue. Spoil heaps at this site have been severely eroded, exhibiting rills and deeper incisional features. Erosional canyons reach up to 8 m in depth with U-shaped cross sections. The sandy, vertical walls of the canyons expose the stratigraphy of the Tertiary delta and offer protected habitat for Sand Martins (*Riparia riparia*). The deeper canyon features originate from upstream networks of steep, V-shaped furrows and rills of 0.5 to 4 m depthspoil. These erosional features exhibit uneven, stepwise profiles with numerous waterfalls of up to 4.5 m height, as well as potholes and intermittent channels. The erosional drainage networks shift after each heavy rainfall. The eroded debris consists primarily of sands that develop into alluvial fans with interbedded fly-ash deposits. Erosion and re-deposition are primarily controlled by the slope angle, the absence of vegetation cover due to an acidic, phytotoxic substrate, and the presence of unconsolidated sands and clays.

The adjacent Medard-Libík mine site offers a stark contrast to the erosional geomorphology of the Silvestr mine. The Medard-Libík mine was abandoned in 2000 and developed erosion features under similar conditions to those observed at the Sivestr site. Reclamation efforts using a clay substrate cover layer and cultivation of a vegetation surface reduced erosion however starting in 2008.

Recultivation Potential of the Overburden Substrate

The success of forest and agricultural recultivation depends on the quality of the substrate on which the vegetation develops. The topsoil layers of spoil heaps in the Sokolov Basin vary widely across a range of different

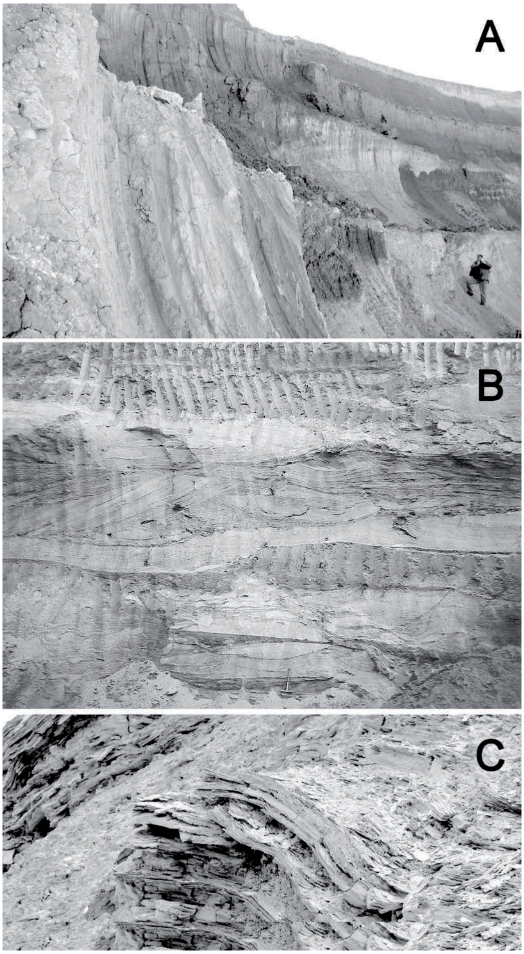

Fig. 4 Examples of various overburden substrates. Kaolinized tuffs of the Chodov Member, Družba coal pit (top), alluvial sands and kaolinized volcaniclastic clays with coal interbeds of the Habartov Member in the Medard-Libík pit (middle), laminated bituminous claystones of the Cypris Formation in the Marie/Jiří pit (bottom) (photograph by P. Rojik 2004).

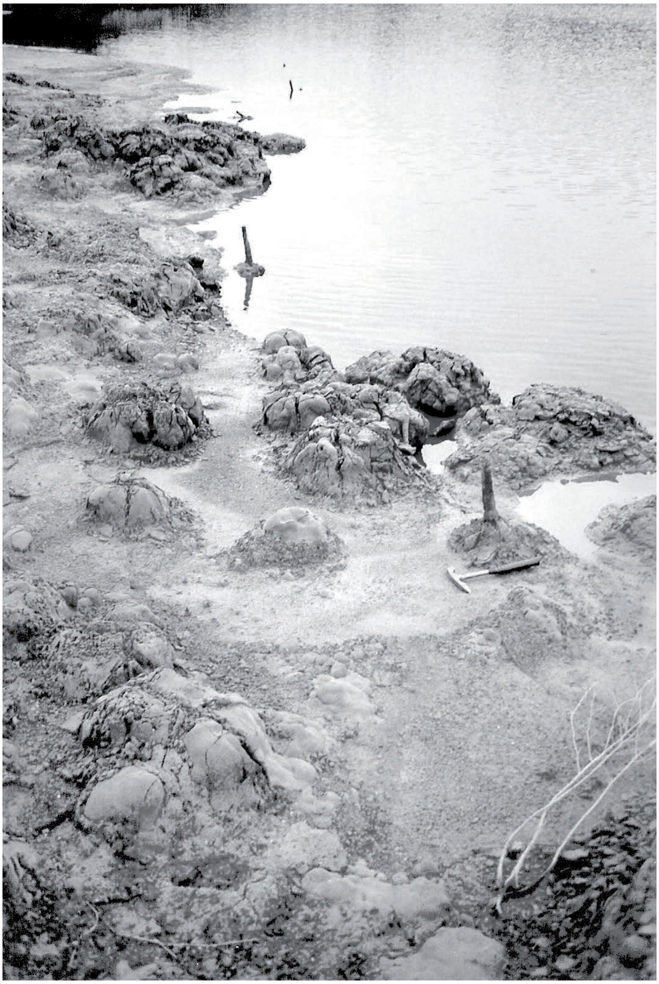

Fig. 5 Recent jarosite-goethite cherts from the former George pit. Photograph by P. Rojík 1998.

properties. Substrate composition and consistency depend on parent rock type and weathering processes related to mining procedures and deposition within the spoil deposit.

Among the most important factors affecting a substrate's reclamation potential are mineralogic composition, nutrient availability, organic matter content, concentration of potentially toxic elements and their speciation, radioactivity, adsorption properties of organomineral complexes, cation exchange capacity (CEC), pH, texture and structure, geochemical alteration trends, infiltration properties and the degree of weathering prior to exposure by mining operations.

Fig. 6 Eroded sediments in a protected natural area that includes the former Silvestr pit mine. Photograph by P. Rojík 2011.

Excavation and transport methods used during mining and re-deposition procedures also affect the spoil deposit's reclamation potential. The excavation process (mechanical shovel, bucket-wheel or bucket chain excavation methods), material transport (conveyor belts with overfalls or wagons, vehicular transport) as it relates to atmospheric exposure and methods of spoil debris deposition (stowing machine, mechanical shovel, bulldozer) that include sealing, leveling, and drainage system design, each influence the physical and chemical weathering trajectory of a given spoil deposit material.

Reclamation efforts in the Sokolov and Most coal districts over the last 60 years have demonstrated which substrates facilitate successful recultivation. These include loess and loess loams, delluvial and alluvial loams, bentonized tuffs, kerogen-rich tuffitic claystones with illite, smectites and admixture of carbonates, zeolites, feldspars and material containing natural aliphatic organic compounds. Materials that diminish recultivation potential include acidic clays containing coal debris, pyrite and marcasite, kaolin and kaolinic clays and leached kaolinized tuffs. Adding a component of the beneficial materials (the former list above) can help stabilize and improve the reclamation potential of a given spoil deposit site. Crushed marlstones, porcelanites, ash and other coal-combustion residues for

Table 1 Recultivation potential of rocks in the Sokolov Basin and their abundance within the spoil heaps. Individual strata is ranked according to total concentration of accessible mineral nutrients (MIN), concentration of phytotoxic compounds (TOX), pH, adsorption and buffer properties (SOR), content and composition of organic substance (ORG), physical and infiltration properties (INF).

STRATIGRAPHIC UNIT **Typical rock**	**Abundance (%)**	**MIN**	**TOX**	**pH**	**SOR**	**ORG**	**STR**
QUARTERNARY **loess loams**	**3**	▒	▒	▓	▒	▒	▓
CYPRIS FORMATION **Top part: weathered claystones**	**12**	▒	▒	▒	▒	░	
CYPRIS FORMATION **Upper part: poly-mineral claystones**	**28**	▒	▒	▓	▓	▒	▒
CYPRIS FORMATION **Lower part: kaolinic clays**	**18**	▒	▒	▓	▒	▒	▒
JOSEF, ANEŽKA AND ANTONÍN MEMBERS **Coal, bituminous clays**	**8**	▒			▒	▓	▒
HABARTOV MEMBER **sands, kaolinized volcaniclastics**	**14**	▒	▒	▒	▒	▒	▒
TĚŠOVICE MEMBER **bentonized volcaniclastics**	**2**	▒	▒	▓	▒	▒	
CHODOV MEMBER **kaolinized volcaniclastics**	**10**	▒	▒	▒	▒		▒
CHODOV MEMBER **bentonized volcaniclastics**	**2**	▓	▒	▓	▓		
DAVIDOV MEMBER, STARÉ-SEDLO FM. kaolins	**3**	▒	▒	▒			

Parameter	**very good**	**acceptable**	**unacceptable**
MIN (mineral nutrients) $CaCO_3$ % conductivity 1:5 in water µScm^{-1} K and Mg [mg.kg^{-1}]	$CaCO_3$ >0.7 K >300 Mg >230	$CaCO_3$ 0.4–0.7 K 110–300 Mg 120–230	$CaCO_3$ <0.4 K <110 Mg <120
TOX (toxic substances) Measured here As [mg.kg^{-1}]	≤10	11–40	>40
pH Measured as exchange pH (KCl)	6.6–7.2	5.0–6.5 7.3–7.7	<5.1 >7.7
SOR (sorption) CEC [mmol.100g^{-1}]	>18	8–17	<8
ORG (non-coal organic matter) C_{ox} [%]	>4	1–4	<1

example can enhance the structure and permeability of a dense, clay-rich substrate. Addition of bentonite, a fine-grained fraction of basaltic material or pond mud can improve retention and stability of permeable sands. Limestone, dolomite, marlstones and ash amendments can stabilize and neutralize the pH values of sulfur-rich, clay and coal residue-bearing debris. An addition of organic-rich material such as compost, pond mud, vegetation litter or animal spoil can also support and enhance microbiological processes in soils.

The following sections qualitatively describe the recultivation potential of typical substrates observed in the Sokolov spoil heaps (Table 1). A quantitative comparison using more rigorous and universally applied analytical methods is in preparation for future publication. The thickness and distribution of each stratigraphic unit and their rock types are shown in Fig. 2.

Kaolinic Substrates

This group of substrates is represented by primary kaolins weathered from gneisses and granites that underlie the Tertiary fill of the Sokolov Basin. These are covered by secondary kaolins deposited in fluvial channels (Figs. 2 and 4) and proluvial sheets at the base of the Tertiary section. Kaolins and other units beneath the main coal seam are exposed mainly along the tectonic margins of the coal-bearing depressions where mine operators have removed material to maintain stable slope angles around the pit. During kaolinic weathering of rocks in acidic environments found in subtropical forests, elements like Na, K, Mg, Ca and Fe leach out of silicate minerals and re-precipitate as the alumina-rich mineral, kaolinite. As feldspars comprised the dominant mineral in basement granites and gneisses, the original crystalline fabric disappeared and was replaced by a bimodal quartz and kaolinite residual material. Transport and redeposition has shifted the quartz to clay ratio to reflect transport energy and sorting capacity of the stream. Kaolinic weathering has diminished the macro- and microelemental nutrient content within the substrate. The low CEC and low permeability of the heavy, clay-rich substrate can complicate reclamation strategies, especially in the case of fractions having very high proportions of kaolinite.

Sandy Substrates

Clastic sediments occur at the base of each Tertiary and Quaternary depositional sequence. Clastic content decreases with time or stratigraphic height up to the coal-bearing horizons. Sands deposited in fluvial channels and alluvial fans surrounding the basin, which periodically prograded into swamps and lacustrine environments situated in the center of basin (Fig. 4). Most of the sand-sized fraction derives from weathering crusts and thus consists of rounded quartz grains with kaolinite rinds and inclusions. The oldest units (Staré-Sedlo Fm.) consist of well-sorted, cemented quartz sandstones and conglomerates that exhibit a relatively high degree of geochemical maturity. Of the younger sands and conglomerates that typically comprise the spoil deposit substrates, the quartz clasts are accompanied by kaolinized feldspar clasts and fragments of granitic and volcanic rocks (Davidov, Habartov, Čankov and Pleistocene units). Sandy substrates are immature, unconsolidated and poorly sorted. The mineral nutrient content is relatively poor whereas toxic element concentrations (As, Hg) are locally elevated. Substrates exhibit a range of acidities due to pyrite weathering. Both CEC and organic matter content (e.g., coalified roots) are low. Physical and infiltration properties of this substrate can facilitate reclamation if the sands contain a sufficient loam fraction.

Coaly Substrates

The coal-bearing units in the study area (Josef, Anežka and Antonín beds) have been mostly modified by historical underground mining operations. The remnants of these bodies typically contain humic coal layers alternating with liptobiolite or sapropelite coal. These deposits include rhythmic intercalations of kaolinized tuffaceous material interpreted to reflect periodic lacustrine flooding. The sedimentary character of these units indicates deposition under aqueous conditions that vacillated between lacustrine and swamp environments. Older spoil heaps include higher proportions of coal and brown, organic-rich material reflecting the sedimentary transition between coal and clay or argillized tuffs. Oxidation of coal debris that includes a high proportion of aromatic organic compounds leads to enrichment in humic and fulvic acids. Production of free phenols and kresols associated with the oxidation impose biochemical limitations on microbial activity. These factors contribute to a relatively high C/N ratio of < 40 to 50 that persists even after several decades (Kříbek et al. 1995). Nutrient content of coaly substrates is relatively low due to the kaolinization and leaching of middle-banks and rocks adjacent to the coal seam. Concentrations of toxic elements (As, Be, Ga, etc.) range from low to very high depending on proximity to and permeability of Tertiary channel features. The coal-rich substrates exhibit a range of acidic pH's depending on their sulfur and pyrite content. The substrates also have extremely low CEC and abundant organic matter consisting from coal often accompaned with substrate hydrofobicity.

Kaolinized Volcanic Substrates

Airborne and reworked pyroclastic materials represent the most common type of fill found in the Sokolov Basin (Fig. 4). These occur within all stratigraphic units and comprise the entirety of the Chodov and Těšovice beds. Volcaniclastic rocks, cinder cone deposits and some lava flows have experienced devitrification, argillization either to kaolinite or montmorillonite, carbonatization (siderite > dolomite and calcite), accompanied by growth of authigene anatase and phosphates. These weathering processes have transformed slaggy and permeable bedded units of originally basaltic composition into soft, impermeable, poorly bedded clay-rich rocks. The trajectory of rock alteration can be approximated by a succession of halmyrolytic processes in an aqueous environment (Kühnel and van der Gaast 1996): cooling → lost of internal stress → jointing → increasing of reaction surface → heating by exothermic reactions (devitrification of volcanic glass, etc.) → growth of clay minerals → expansion caused by hydration and crystallization → deformation and fragmentation of rock → collapse of rock structure. Units in the Sokolov Basin typically exhibit alternating volcaniclastic and sedimentary coal-bearing beds (Fig. 2). Soils and peat bogs developed during interludes between periods of volcanic activity. In the vicinity of organic matter multicolored volcanic deposits (Fig. 4) undergo reduction, bleaching, acidification and leaching processes. The nutrient content of volcanic kaolinized substrates is therefore relatively low. Concentrations of toxic elements are not elevated except within marginal areas of the basin that host active transport of U, Be, Ge, Ga and REE from adjacent uplifted granites and U-deposits. The pH of the volcanic substrate is slightly acidic and CEC is very low. Organic matter is locally abundant but compositionally inadequate for recultivation (frequent thin coal beds, coalified roots). The substrate also has levels of clay content that hinder physical and infiltration properties necessary for reclamation.

Bentonized Volcanic Substrates

The geological history of the bentonized volcanic substrate is similar to that of the kaolinized volcanic units except that the bentonized material did not develop in contact with organic matter and did not experience acid leaching. Although bentonites occupy the same stratigraphic position as the kaolinized volcaniclastics, the former unit occurs along the rim of the coal-bearing basin and within thick volcaniclastic sequences that are closely associated with volcanic features. Basaltic lavas and volcaniclastics exhibit devitrification, argillization to montmorillonite with an admixture of kaolinite, carbonatization, crystallization of anatase, zeolites and phosphates. All basalts and argillized volcaniclastics are enriched in elements associated with alkaline volcanism (Ti, V, P, Th, Ba, Sr, REE, etc.). Bentonitic volcaniclastic substrates contain relatively high proportions of nutrients and low concentrations of toxic elements. Their pH is neutral to slightly alkaline and their CEC high to very high. Organic matter is scarce with the exception of coalified roots and woody material found in the Těšovice Beds. The physical and infiltration properties of this substrate are poor given its relative proportion of clay material.

Cypris Substrates

The Cypris Formation forms the dominant part of the overburden material from the coal pits. The base of the formation consists of grey, thin-bedded, kaolinitic clays and silts deposited in a permanent freshwater lake. Deposition of polymineral claystones continued with the development of brackish intermittent meromictic lakes. Intercalated carbonate crusts (dolomite > ankerite, calcite) indicate episodic desiccation. The dense mixture of fine-grained terrigenous and volcanic material in the Cypris Formation suggest slow accumulation in a low energy sedimentary environment. Depositional features reflect a warm, arid climate. The diagnostic sediments are thin-bedded mudstones with horizontal or lenticular laminations (Fig. 4). The basal units consist almost exclusively of kaolinite with illite developing in upper layers along with dispersed and nodular Ca-, Mg-, Fe-, Mn-carbonates, montmorillonite, analcite, K-feldspars, K-zeolites, anatase, quartz, micas, greigite, pyrite, gypsum, thénardite and algal and pollen-derived kerogen bound organic matter. The fine lamination and lack of bioturbation at the sediment-water interface indicate a permanently stratified water column subject to periodic eutrophication. Three different iron sulfide-bearing zones demonstrate euxinic conditions affecting the lake bottom: nodular pyrite and dispersed ferromagnetic greigite, smythite and pyrrhotite. Evaporites, efflorescent Na- and Ca-sulphates forming in spring environments, high boron contents, remnants of halophytic algae, salt-tolerant fish and sulfur isotopes demonstrate periodic arid conditions.

The Cypris Formation includes substrates that facilitate reclamation and recultivation. The mineral nutrient content is relatively low at the base of the Cypris Formation but increases in a stepwise fashion with the occurrence of carbonates, illite, smectites and authigenic K-minerals. Concentrations of toxic elements are persistently low with the exception of several horizons in which pyrite and greigite weathering contribute to acidity. The pH values reflect slightly acidic conditions within the basal kaolinic clays but increase to neutral and even alkaline conditions with the appearance of carbonates and analcite. The pH decreases again to slightly acid values in the uppermost weathered and leached section of the unit. The CEC and buffer capacity increase from average values at the base of the unit to relatively high values in the middle and upper part of the formation. Dispersed organic substances are abundant from the base of the formation to mudstones in its upper regions. The algal and pollen-derived kerogen contains a relatively large aliphatic fraction which facilitates microbial activity and stabilization of the C/N ratio to values of 10 over the last 35 year period (Kříbek et al. 1995). These factors, along with the physical and infiltration properties of thin shale beds in the broad, middle zone facilitate recultivation. Shale layers may disintegrate to clay after seven to eight years with irrigation. The basal and weathered zones of the Cypris Formation contain heavy clay substrates and are thus unsuitable for some reclamation methods.

Loam Substrates

Loess loams and delluvial loams of Pleistocene and Holocene age occur as remnants in the disturbed landscape. Their mineral nutrient content is relatively high except for units composed of gravel river terraces. Concentrations of toxic elements are relatively low and pH values reflect slightly acidic to neutral conditions. CEC values fall within the average to enriched range and organic matter content is relatively low with local exceptions. The physical and infiltration properties of the substrate are ideal for reclamation and recultivation methods.

Conclusions

Since the initiation of intensive coal mining operations in the Sokolov Basin during the 19th century, the originally flat landscape has transformed into a complex surface of hills and basins covering an area of more than 100 km^2.

This landscape consists of inner and outer spoil heaps that have undergone rapid physical and chemical alteration processes and developed pronounced vertical zonation.

Acid leaching within open pits and spoil sites leads to precipitation of secondary jarosite, schwertmannite, ferrihydrite, lepidocrocite, goethite, gypsum, calcite and other phases.

Open pits have developed oligotrophic surfaces and undergone routine ecological succession to become a biologically diverse landscape that hosts a range of protected plants and animals.

The most effective substrate for recultivation among the different types of spoil deposit material are the polymineralic carbonate claystones of the upper Cypris Formation, the bentonized volcaniclastics of the Chodov Member and the loess loams. Conversely, debris containing a high proportion of residual coal, acidic, leached-out kaolinic clays, or kaolinized volcaniclastics exhibit poor reclamation potential.

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CHAPTER 2

Humus Accumulation and Humification during Soil Development in Post-Mining Soil

Evgeny Abakumov[1,*] **and** ***Jan Frouz***[2]

Introduction

Soil formation is a result of an interaction of five factors: climate, biota, relief, parent material and time (Dokuchaev 1949). Accumulation of organic matter and its downward migration in the soil profile play major roles in soil formation (Abakumov 2008, Cerli et al. 2008). Accumulation of organic matter leads to formation of an organic layer and affects many soil properties such as water holding capacity, C or N content, soil biota, etc. The humification process involves the main agents of soil weathering, chelatization and complexation of soil mineral compounds, and migration and translocation of organo-mineral compounds. The quality of organic matter (Kononova 1966, Ponomareva and Plotnikova 1980, Andreux 1996) and the soil biota (Ponomareva and Plotnikova 1980, Emmer and Sevink 1994, Androkhanov et al. 2000, Abakumov 2008) determine soil formation.

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Humic acids (HAs) are insoluble in water and do not migrate intensively in the soil profile. Fulvic acids (FAs) are a mobile group of soil organic components, which is characterized by a high degree of solubility in water, a strong ability to react with minerals and cations, and high mobility in the soil profile. FAs are the main agents of soil mineral weathering, while HAs are most important for the formation of soil aggregates through the process of organo-mineral stabilization (Kogel-Knabner et al. 2008). The relationship between soil formation and humus accumulation is the tightest in very initial stages (Zavarzina et al. 2007).

Most soil scientists have studied soil formation using soils of Holocene age (i.e., 8,000–12,000 years). Our knowledge about soil formation is therefore based mostly on retrospective interpretation of soil chemistry and morphology (Hitrov 2008). Another approach is to study ongoing soil formation. Chronosequences, or sets of plots of known different age, are the most useful for such studies (Alexandrovskiy and Alexandrovskaya 2005, Huggett 1998) and particularly for studies of interactions between chemical and biological soil properties over time (Frouz and Novakova 2004). Chronosequences allow us to study soil development in young soils (Bowman 1989, Huggett 1998, Lichter 1998, Egli et al. 2001, Gillot et al. 2001, Buurman et al. 2008). This is particularly valuable since the rate of pedogenesis is reported to be rapid in the first 50–60 years followed by a decrease whereas the quasi-equilibrium stage emerges after 1,500–2,000 years (Alexandrovskiy and Alexandrovskaya 2005). The chronosequence approach has been used to study volcanic soils, soils created by retreating glaciers (He and Tang 2008) and also soils at post-mining sites (Frouz and Novakova 2004).

During open-cast mining, large amounts of material called spoil or overburden overlaying the mined mineral resource is excavated and placed either back into the mining pit or in thick layers outside it. Post-mining substrates are often of extreme texture and pH. They lack recent organic matter but may often contain fossil organic material (Bradshaw 1997).

Soil can develop directly from the spoil heap substrate, which takes place under the influence of vegetation and other pedogenetic factors (Frouz et al. 2009). In other cases, overburden can be covered by recent soils salvaged before mining. Alternatively, it can be improved with different amendments such as various waste products (composts, lignogumates, organic waste) or salvaged materials (sod or umbric horizons), promoting soil development (Sydnor and Redente 2002, van Rensburg and Morgenthal 2003, Mercuri et al. 2005, Perminova et al. 2006, Kapelkina 2009). Amendments usually contain organic matter. Reclaimed materials, nevertheless, need to be neutralized or deoxidized. Limestone, for example, has been used to neutralize pyrite-acid grounds, and sands or products of granite crushing have been used to improveme the aeration of overmoist