Public document

Environmental Assessment of Sokolov Lignite Mines using Remote Sensing

Progress Report

BRGM/RP-56472-FR
December, 2007

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ČESKÁ GEOLOGICKÁ SLUŽBA

Sokolovská uhelná, právní nástupce, a.s.
SOKOLOV

Geoscience for a sustainable Earth
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Study carried out as part of
Research activities - BRGM 2007

S. Chevrel, V. Kopačková, A. Bourguignon, V. Metelka
With the collaboration of
P. Rojík

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Sokolovská uhelná, právní nástupce, a.s. SOKOLOV

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Synopsis

This report presents the preliminary work done in 2007 in collaboration between the Czech Geological Survey (CGS) and BRGM, the French Geological Survey, with the participation of the mining company Sokolovsá Huhelná a.s., over the lignite mines of the region of Sokolov, Czech Republic.

This collaboration was initiated by the CGS in the frame of its "Remote Sensing based Assessment of Mining Impact of Sokolov Basin" project and, from BRGM side, carried out in the frame of the BRGM's "post-mining" RTD project APRM-03.

Mines (abandoned, still-active) are one of the most challenging environmental problems faced by government, communities and mining industry worldwide. Mineral spectroradiometry, both from airborne or spaceborne sensors and ground measurements, represents an alternative to conventional methods and efficient way to characterize mines and assess the potential for AMD discharge (Acid Mine Drainage).

The work carried out consisted in a preliminary field reconnaissance of the Sokolov lignite open-cast mining area and its surroundings and in a field spectroradiometric campaign using the BRGM's FiedSpec 3 portable spectroradiometer.

High-altitude spectroradiometry (ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer satellite data) together with ground-based spectroradiometry (ASD Filedspec® spectroradiometer) were applied in order to define the capability for identifiying the locations of the most significant sources of AMD discharge at the Sokolov open-pit mine site.

Once resampled to ASTER spectral bands, spectroscopy measurements have shown that:

- Iron oxy-hydroxides showed diagnostic absorption before in the visible and the NIR, in this particular case at the wavelength of 0.8070 µm (ASTER band 3). This absorption feature was found to be more visible on the hematite group minerals, on the other hand, the goethite minerals showed more distinctive spectral feature at 0.661 µm (ASTER band 2).
- Jarosite mineral group, as Na-jarosite and ammonio-jarosite, has similar spectral properties in the visible-NIR region as the iron oxy-hydroxides, but shows supplementary absorption feature at 2.167 µm (ASTER band 5).
- Clays are the most common minerals at the open pit mine site, thus can be found in different geological materials as a part of intimate mixtures. They have the most distinctive absorption feature near 2.209 µm (ASTER band 6).

First results comparing the mineral maps derived from ASTER imagery with field investigations, confirmed with XRD analyses, demonstrated the ability of spectral remote sensing in mapping mineral species such as secondary iron minerals. Image process-

ing identified jarosite as a part of the mixture material in accordance with conducted XRD analyses.

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1. Introduction

1.1. THE PROJECT

The CGS contacted BRGM in March 2007 in view of the submission in 2008 of an international cooperation project to the Czech Foundation for Science, together with the EU DG Joint Research Centre, Institute for Environment and Sustainability and the Martin Luther University of Halle – Wittenberg.

BRGM and CGS also submitted a proposal for a 2008 bilateral cooperation in the frame of the PHC (Parthership Hubert Currien) Barrande funding scheme.

BRGM and CGS decided to start their collaboration over the Sokolov lignite mine area in 2007, in the frame of their respective self-funded RTD projects.

BRGM carried out a two-week visit in Czech Republic in September for two remote sensing specialists, while the Czech project leader visited BRGM in November.

The purposes of these first contacts were to proceed to:

- a preliminary field reconnaissance of the Sokolov lignite open-cast mining area and its surroundings by the BRGM team together with CGS's remote sensing staff. The geologist of Sokolovsá Huhelná a.s. accompanied the visit, as well as other specialists of the mining company;
- a field sampling campaign;
- a field spectroradiometric campaign using the BRGM's FiedSpec® 3 portable spectroradiometer;
- Very first image processing of available superspectral ASTER imagery.

More in-depth processing of these ASTER images will take place in 2008 together with the processing of hyperspectral images of the lignite mines, if made available to the project in 2008.

1.2. THE SOKOLOV LIGNITE MINES

1.2.1. Geographic setting

The Sokolov lignite mining area is located in the North-West of the Bohemia province, west of the town of Karlovy Vary, close to the German border (Illustration 1).

Topographic maps (Appendix 2) show the area is largely affected by mining activities: open casts and dump sites.

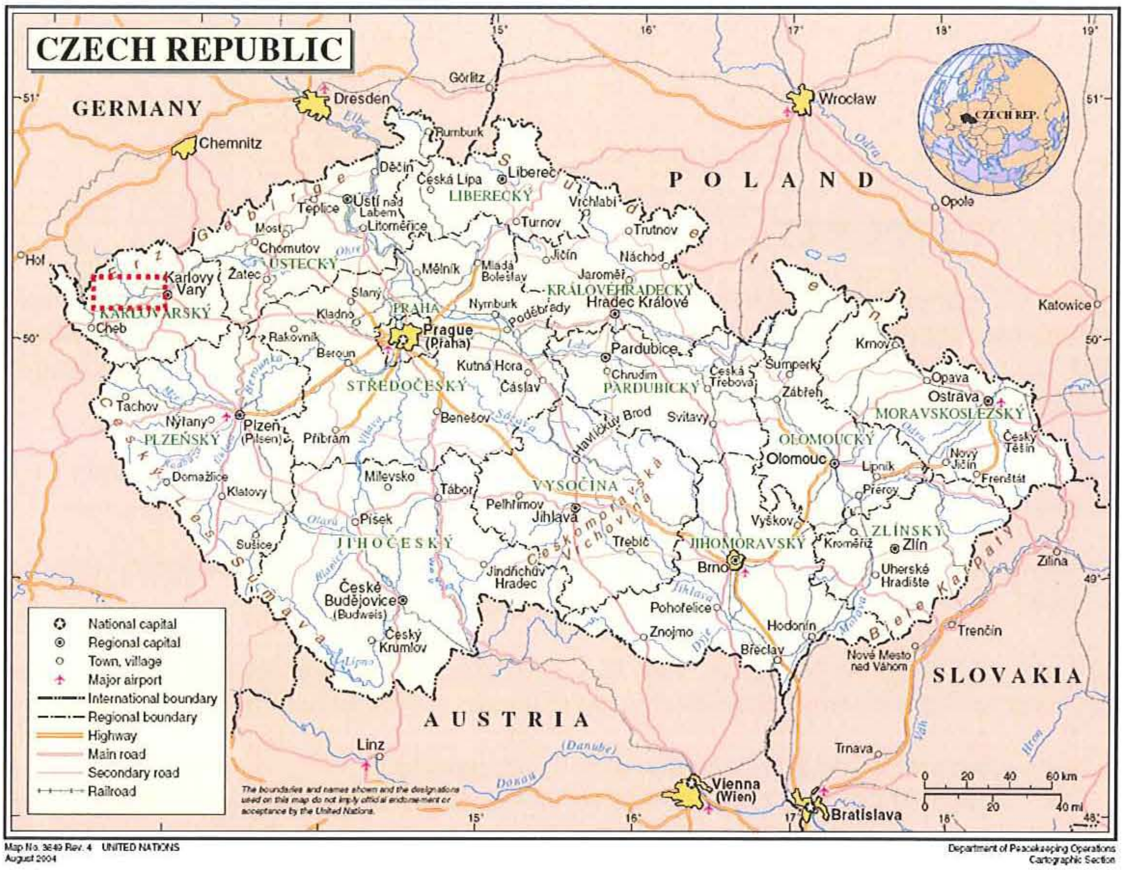


Illustration 1: Study area (dashed red quadrangle)

The area is hilly, ranging from 400 to 750 m in altitude (Illustration 2 and Appendix 3), the basin is drained by the Ohre river. Illustration 2 clearly enhances the morphology of the Sokolov graben and highlights the active and abandoned open pits (in pale blue), corresponding to the lowest areas. Apart from the mined areas, the region is mostly devoted to agriculture and hilly areas are covered by forest (Illustration 3). The mining works appear in whitish on this image while the exposed brown coal appears in orange

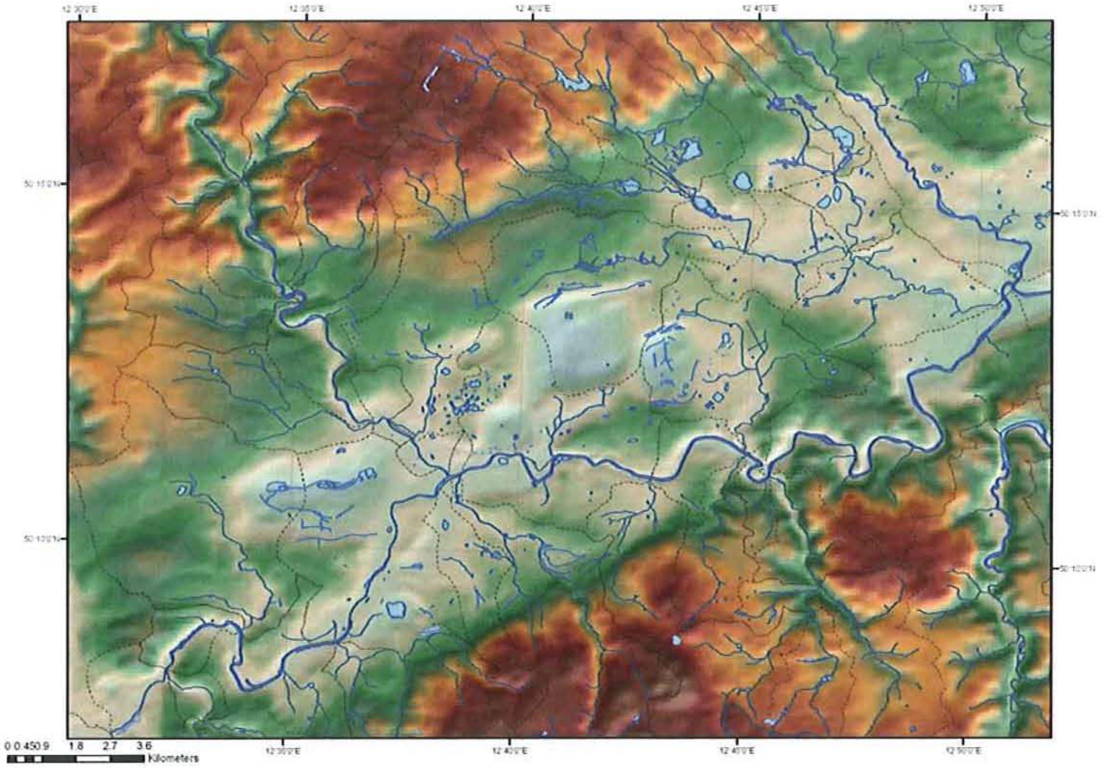


Illustration 2: SRTM shaded relief of the study area

Illustration 3: Land cover and inahited places in the study area

1.2.2. Geologic setting

The Sokolov basin is part or the Eger rift (Illustration 4) that was strongly rifted into numerous hosts and grabens (Rojík *et al*, 1998) and gave rise to several brown coal deposits (Illustration 5) in Czech Republic, Germany and Poland.

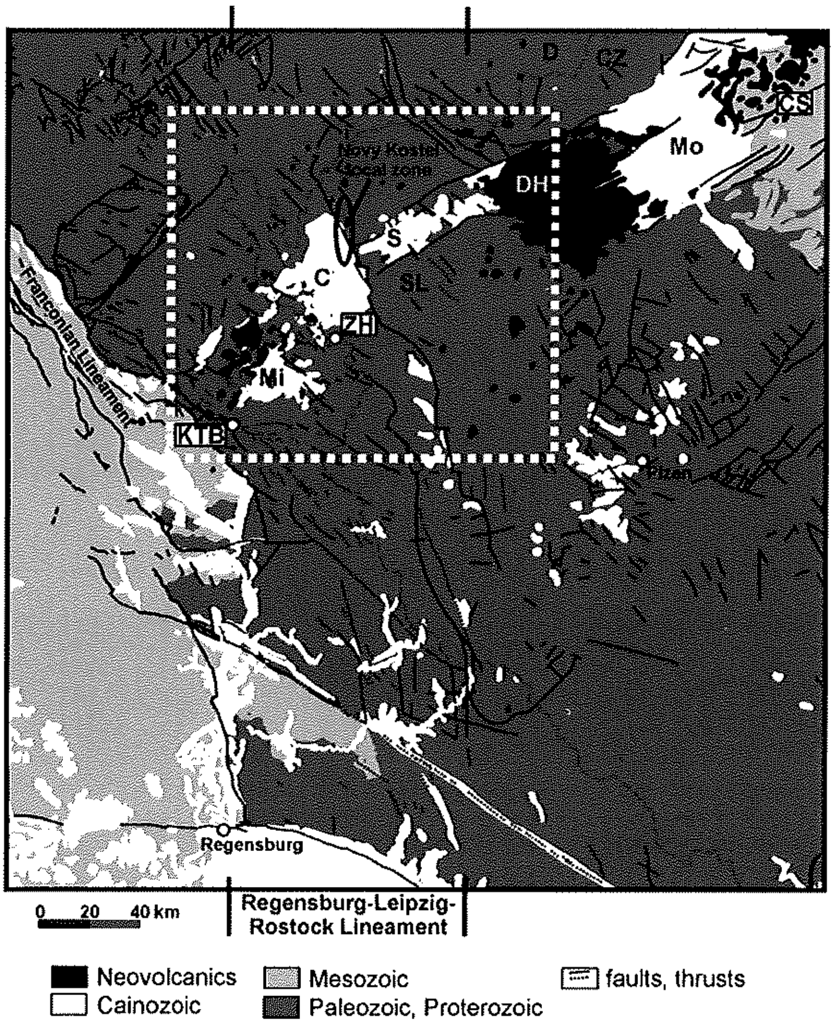
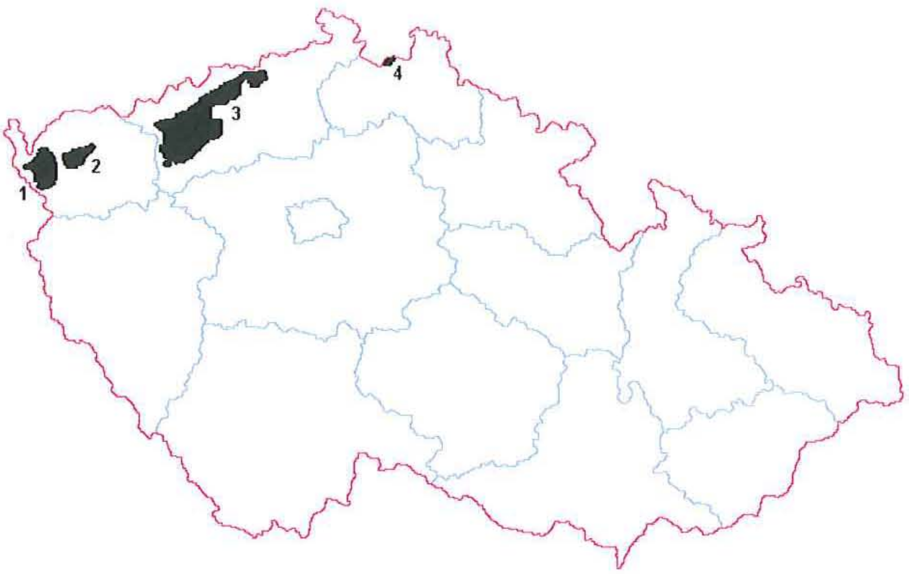


Illustration 4: Distribution of Tertiary-Quaternary volcanic fields and sedimentary basins in the western part of the Bohemian
The WSW-ENE striking line of the sedimentary basins: Mitterteich (Mi), Cheb (C), Sokolov (S), and Most (Mo) basins as well as the volcanic fields Doupovske Hory (DH) and Česke Středohoři (CS) belong to the Eger (Ohře) Rift. KTB = location of the German Continental Deep Drilling Boreholes; ZH – Železná Hůrka volcano, Quaternary (sample location for mantle xenoliths), SL – Slavkovský Les



1 Cheb Basin; 2 Sokolov Basin; 3 North Bohemian Basin; 4 Žitava Basin

Illustration 5: brown coal deposits in the Czech republic

The development of the Sokolov basin was accompanied by extensive alkaline volcanism and hydrothermal activity. The tertiary volcano-sedimentary complex of the Sokolov basin is up to 350 m thick and contains three extractable lignite seams : Josef (Oligocene), Anežka and Antonín (Miocene). The basement of the basin consists of a crystalline complex and granites of a Hercynian mountain belt that has undergone major denudation since the Permian, with Kolinitic weathering during the Cretaceous and Paleogene (Murad and Rojík, 2003)

1.2.3. History of mining

In the Sokolov basin, mining for bituminous slates at the rims of lignite seams, which are extremely rich in pyrite and marcassite, was initiated in 1642 for the production of vitriol, alum and sulphuric acid. Extraction of lignite for combustion began in 1793. From 1890 large-scale underground and surface mining operation attracted numerous industries and economic development, but eventually led to considerable environmental problems in the region (Murad and Rojík, 2003).

The territory of Karlovy Vary, Sokolov, Krušné Hory and Slavkovský Les regions, is well known for its long-term and intensive mining of lignite, which causes a significant material transport and various changes in the landscape and the environment, in general.

Study area includes Sokolov Basin, Krušné Hory Crystalline Complex and Karlovy Vary Massif. In the past, the territory was also well known for Uranium, Tin and other polymetallic deposits and feldspar mining. Another precious natural resource of the area are mineral and thermal springs used for curative and drinking purposes.

The open-cast mining is carried out in benches (Illustration 6), and as the earlier sections are mined, fresh areas are successively stripped. This is accompanied by several environmental problems, such as the following:

- lcal changes in morphology, landscape and drainage and degradation of land use due to dumping of material
- Erosion of bare of thinly vegetated dump slopes
- Acid Mine Drainage (AMD) and discharge of highly mineralized waters from mine dumps and contamination of surface and subsurface water
- Vegetation stress due to contamination of air, soil, and water
- Limitation of mining due to established protective zones of the mineral and thermal springs

Illustration 6: bench-type exploitation of the lignite at the Jiží mine

Illustration 6 shows the bench-type exploitation at the Jiží mine: yellow orange carbonates (top layer) and grey clay overburden are first removed and dumped via conveyor belts in already exploited part of the mine; brown- coal (bottom) is exploited once overburden removed.

Close to the mining area is located the most famous Czech spa town of Karlovy Vary. Therefore the environmental and protection problems related to the mining activities and exploitation of the water resources should be observed in detail and monitored regularly.

2. Geology and Mining

2.1. GEOLOGY OF THE SOKOLOV BASIN

2.1.1. Generalities

The Sokolov basin consists in a SW – NE oriented "graben" (Eger rift) between the Morni Slarkov and the Krušne Hory neoproterozoic complexes (phyllites and metamorphic rocks) that form the mountains North (Erzgebirge) and South of the basin (Illustration 7). The units have been intruded to the East by the NW – SE Karlovy Vary batholith of Variscan age.

The Sokolov basin, Oligocene to Miocene in age, extends over 8 to 9 km wide and 36 km long with a total area of about 200 km^2. The basin comprises 60 % volcanic ejecta resulting from faults and volcanic cones and 40 % sediments. It is bordered by complex SW – NE faulting system and is cut by NW – SE faults. Lignite is found only in the western part of the basin.

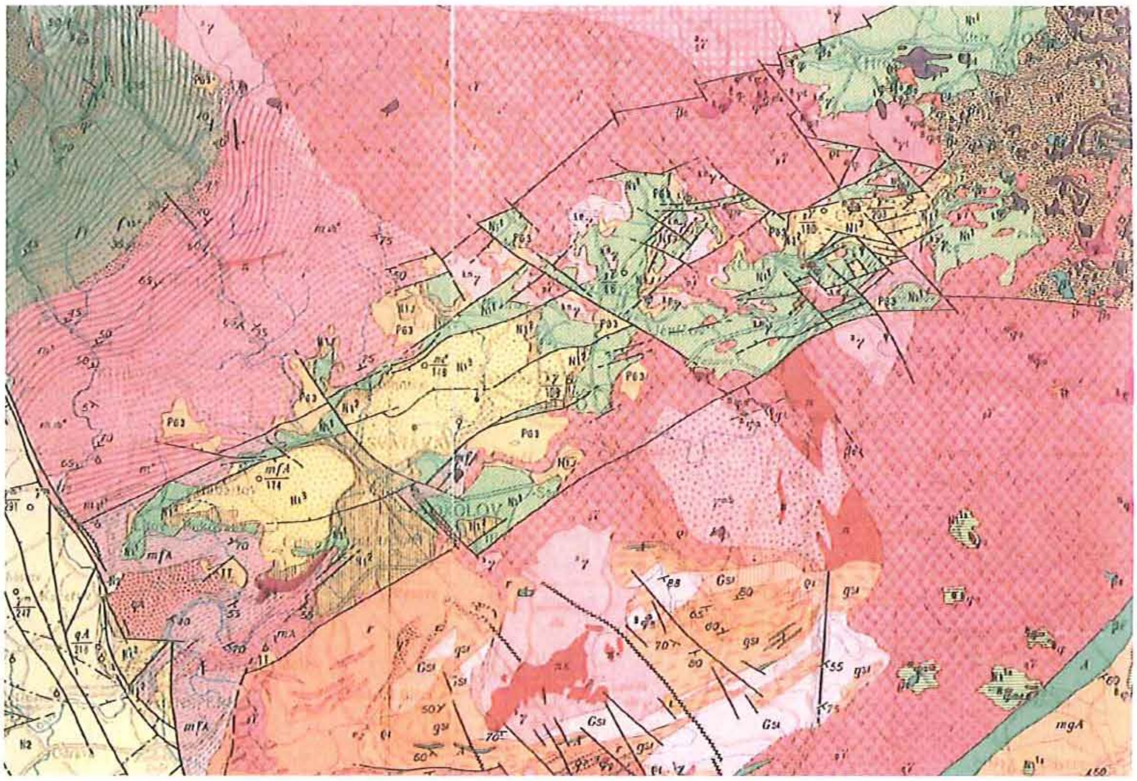


Illustration 7: geological map of the Sokolov basin and surroundings

The basin is limited to the North by the Lipniza faulting system. Hydrothermal fluids have been circulating along the faults where silicification and sulphur are found, and exposures of the latter can result in Acid Mine Drainage (AMD).

In the NW, the boundaries of the basin were formed by crystalline schists and granitoids of the Krušné Hory Mountains, in the SE, by similar rocks of Karlovy Vary Highland. Transverse faults divide the basin into the three main parts (Illustration 8). The basin's basement mainly represents the Karlovy Vary granite massif, the western part is occupied by mica-schists. During the Mesosozoic and Paleogene epoch, the crystalline basement was exposed to kaolinic weathering, which was enhanced by hydrothermal activity along the tectonic zones during tertiary volcanic activity. Of major importance are the brown coal (lignite) sedimentary layers.

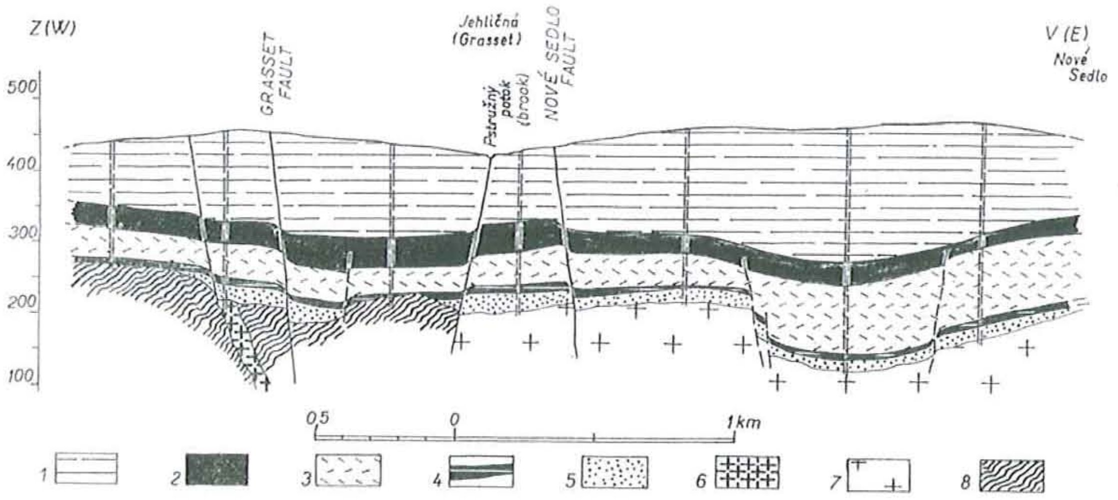


Illustration 8: Cross section through the central part of the Sokolov Basin (according Šantrůček 1962) :
1-4 Miocene: 1-Cypris claystone, 2-Main Seam Formation, 3-Volcanogenic Series, 4-Josef-seam formation, 5- Oligocene, Stare Sedlo layers, 6- Karlovy Vary pluton

2.1.2. Stratigraphic scheme of the Sokolov basin

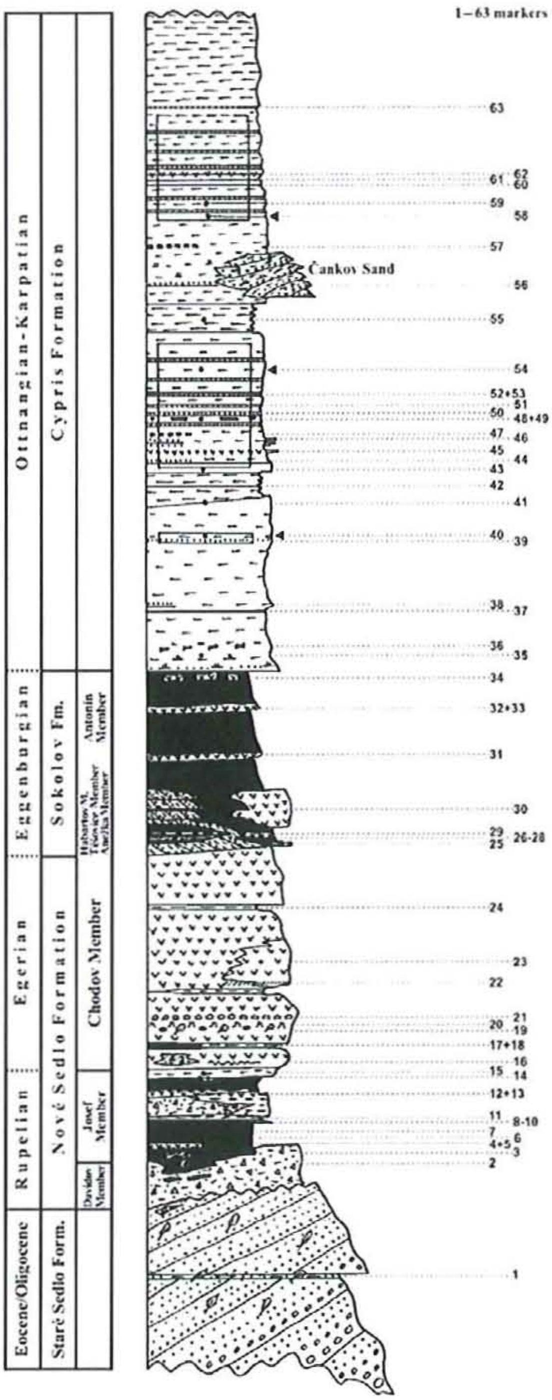
P. Rojík (2004) proposes a new stratigraphic scheme of the Sokolov basin (Illustration 9). A detailed geological map and structural features is presented in Appendix 4

Chrono-stratigraphy	Formation	Member	Characteristic rocks	Typical environment
Holocene			antropogenic deposits, fluvial loams, peats, porcelanites	antropogenic, fluvial
Pleistocene		nine local terrace benches	gravels, loams, loess loams, block fields, peats, porcelanites, mineralized faults	fluvial, eolian, solifluction
unconformity				
			laminated claystones illite-montmorillonite-kaolinitic, admixtures of Ca-Mg-Fe-carbonates, Fe-sulfides, analcite and bitumen; often diastems	lake-playas complex
Bardigalian	**Cypris Formation**	**Čankov Sand**	sands, silty claystones	delta
Ottnangian-Karpatian			laminated claystones illite-montmorillonite-kaolinitic, admixtures of Ca-Mg-Fe-carbonates, Fe-sulfides, analcite and bitumen; diastems	lake-playas complex
			laminated kaolinitic clays, admixtures of siderite, sulfides or sulfates	permanent lake
		Antonín Member	humic coal; local diastems	mires
Bardigalian *Eggenburgian*	**Sokolov Formation**	**Těšovice Member**	bazaltic rocks, tuffs, tuffites, sediments of gravity flows (altered)	volcanic, gravity flows
		Anežka Member	sapro- and liptodetritic coal	mires
		Habartov Member	sands, sandy and silty clays (bioturbated)	fluvial, swamps
disconformity				
Chattian – Aquitanian *Egerian*		**Chodov Member**	bazaltic rocks, tuffs, tuffites (altered)	volcanic, swamps, lakes
Rupelian	**Nové Sedlo Formation**	**Josef Member**	sapropelitic and humic coal; local diastems	mires
Oligocene		**Davidov Member**	clayey sands / sandy clays with gravel admixture – unsorted, unbedded; local diastems	creep, fluvial
disconformity (tectonic movements and hydrothermal activity)				
Upper Eocene – Lower Oligocene	**Staré Sedlo Formation**		sands and sandstones, gravels and conglomerates, locally clays - sorted, bedded; diastems	fluvial
local disconformity				
Paleogene			kaolins and silica rezidues of metamorphites and granites	weathering
unconformity (tectonic fracturing and hydrothermal activity, Triassic - Cretaceous)				
Upper Proterozoic - Upper Carboniferous	Saxothuringian Unit: polymetamorphosed crystalline complexes – the Ohře, Krušné hory, Slavkovský les and Thüringen-Vogtland units and the Karlovy Vary pluton			

Illustration 9: stratigraphic scheme of the Sokolov basin

2.1.3. Stratigraphic column

THE SOKOLOV BASIN:
STRATIGRAPHIC SCHEME OF THE TERTIARY



Explanation:
MB = marker bed
CMB = composite marker bed
MH = marker horizon

63 CMB Pellet limestones
62 CMB Analcime claystones
61 MB Convolution horizon
60 MB Black shale horizon
59 CMB Upper pelocarbonates
58 CMB Upper magnetic horizon
57 MB Upper magnetic chert
56 MB Phlogopite horizon
55 MB Banded claystones
54 CMB Middle magnetic horizon
53 CMB Sulfur layers
52 MB "Double-layer" (green clay + pelocarbonate)
51 MH Grid horizon (pelocarbonate)
50 MB Pyrite ridges (pelocarbonate)
49 CMB Lower pelocarbonates
48 MB Upper fish horizon
47 MB Lower magnetic cherts
46 CMB Upper shale horizon
45 MB Tuffite coloured horizon
44 CMB "Twins" of the greigite horizon
43 MB Accompanying blue-grey clays
42 MB Papery shale
41 MH Colour boundary
40 CMB Lower magnetic horizon
39 MB Greigite horizon
38 MB Lower shale horizon
37 MB Companion (bituminous claystone)
36 MB Fish zone I. B
35 MB Blue-grey clays
34 MB Intercalation "18 inches" (Antonín seam)
33 MB Green clay intercalation (Antonín seam)
32 MB Intercalation 8 (Antonín seam)
31 MB Intercalation 20 (Antonín seam)
30 MB Intercalated Seam (Habartov Member)
29 MB Middle intercalation (Anežka seam)
28 MB Intercalation 30 (Antonín seam)
27 MB Tuffite horizon (Anežka seam)
26 MB Intercalation 35 (Antonín seam)
25 CMB Pelosiderite horizon (Antonín Member)
24 MB Upper coal horizon
23 MH Main red beds
22 MB Laminated red beds
21 MB Pumice stone horizon
20 MH Stock horizon
19 CMB Fossil plant horizon
18 MB Lower coal horizon
17 CMB Intercalated Seam (Chodov Member)
16 MH Basal red beds
15 MB Sulfide bed
14 MB Silica roof (Josef seam)
13 MB Tuffitic claystone (Josef seam)
12 CMB Tonstein beam (Josef seam)
11 MB Bituminous claystone
10 MB Sandstone bank
9 MB Pyrite roof (Josef seam)
8 MB Stone roof (Josef seam)
7 MB Middle bright coal (Josef seam)
6 MB Cube (Josef seam)
5 MB Allochthonous coal (Josef seam)
4 MB Tuffite intercalation (Josef seam)
3 MB "Big intercalation" (Josef seam)
2 MB Basal sapropelitic coal (Josef seam)
1 MB Black sandstone

Illustration 10: stratigraphic column of the tertiary in the Sokolov basin

The stratigraphic column (Illustration 10) after P. Rojík (2004), in particular highlights the three brown coal seams, respectively the Josef member, and the Anežka and Antonin members and the thick overburden represented by the clays of the Cypris Formation capped by limestone. The Cypris clays are dominantly kaolinite at base, passing to illite and montmorillonite (smectite) to the top. Antonin brown coal and Cypris formation can be seen on the photograph in Illustration 6.

The Josef coal seam represents the lower seam, just over the basement rocks. It is very rich in sulphurs (up to 5%). It is a detritic coal made of plants in a former wetland. It contains 60 – 70 ppm of arsenic.

The seam Anežka is more recent than Josef seam and is developed only in the western part of the basin.

The Josef and Anežka seams have been exploited in particular in the Medard open pit.

The Antonin seam is currently exploited in the Jiží open pit. It contains up to 8 % sulphurs together with arsenic

2.2. MINING OF THE SOKOLOV BASIN BROWN COAL

The exploitation of the lignite started from the west: Medard pit, Lomnice pit. Appendix 6 shows the actual extension of the mining works.

The Lomnice pit was exploited in the early 20th century. The coal contained about 5.5 % of sulphur. The Medard pit was exploited over 90 years, with a rate of eight million tons a year of lignite.

Most of the overburden from the past has been dumped over the basement, North of the Chodov – Lomnice road. The dump is 36 m thick in average and mostly constituted of clays from the Cypris Fm. Some levels are rich in organic matter giving rise to brown levels. The clays contain few pyrite and ferro-magnesian minerals, responsible for magnetic anomalies.

10 million tons a year are currently exploited at the Jiží mine.

Illustration 11: exploitation at Jiží mine

Illustration 11 shows the basement micaschists and gneiss (bottom right orange material) north of the Lipniza fault. The fault more or less follows the conveyor belt on the front of the image. The carbonate layer (pale yellow) and clay layer (grey) of the Cypris formation are scrapped on the western part of the mine and backfilled (through conveyor belt transport) over already exploited areas to the west (flat grey area left of the image).

The Antonin seam is exploited in the central part of the pit and conveyed to plants or trains by conveyor belts. The coal at the bottom of the mine is under the water table of the basement aquifer where water is circulating through the faulting system.

Among the 10 million tons exploited yearly (In 2007, 10 million tons of lignite have been extracted and 30 million tons of overburden material removed), 2.25 are burned for local electricity production, 2.5 for the production of steam (heating of surroundings inhabited areas, including Sokolov and Karlovy Vary). The rest is used for domestic market, export to Germany and Hungary, chemical industry.

3. Environmental impact of the mining activities

The mining of brown coal is accompanied by several environmental problems, including:

- Degradation of land use to dumping of mine spoil
- Erosion of bare of thinly vegetated spoil dump slopes
- Local changes in morphology, landscape and drainage
- Discharge of highly mineralized waters from mine sumps and contamination of surface and subsurface water
- Vegetation stress due to the contamination – air, soil, water
- Limitation of mining due to established protective zones of the mineral and thermal springs

The field visit (observation and measurements points are shown in Appendix 5) enabled the CGS – BRGM team to familiarize with the local context and associated environmental problems.

3.1. ACID MINE DRAINAGE

The area is largely affected by Acid Mine Drainage (AMD) due to the presence of sulphur:

- In the brown coal itself: 5 to 8 % pyrite in the coal
- In the hydrothermal deposits along the faulting system that borders the basin and that is affected by the exploitation.

The main AMD-related minerals present in the Sokolov mining area and their respective effluent pH are listed below (after Rojík, personnal communication, Murad and Rojík, 2003)

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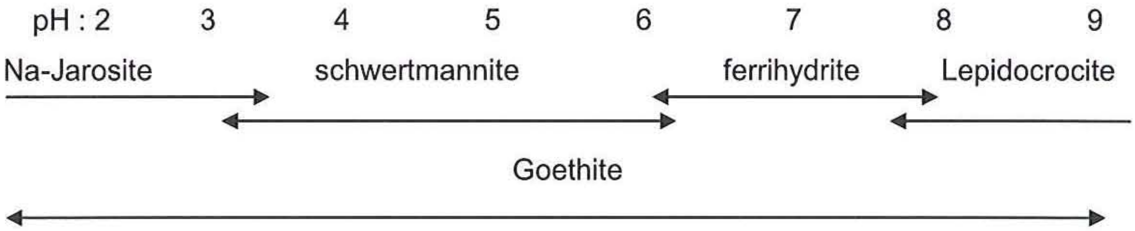

AMD affects the mine waters in the former exploited open pits. Low pH have been measured in the abandoned Lomnice pit (pH = 2.2 at observation point SO 16) with the presence of Na-Jarosite). Several abandoned pits (Lomnice, Medard, Marie, ...) present intensive AMD and low-pH waters, both on the pit slopes ("acid springs") and at pit lakes ("acid lakes", Illustration 12)

Illustration 12: AMD at abandonned pit, east of Lomnice (observation point S0 33). pH = 3.5

AMD also occurs locally on dump sites (Illustration 13). Despite the dumped material consists mostly of Cypris clays, locally some AMD-generating material (coal and/or material from hydrothermal zones) has been dumped. "Acid springs" and/or "acid lakes" have been found in several places during the field visit (SO 5, SO 6, SO 7 and SO 28). It seems there could be an artificial "perched" water level inside the dump that could witness of an indurated "impervious" level.

Illustration 13: "acid spring" flowing out the dumped Cypris material (observation point SO 6)

3.2. COAL FIRES

Coal fires occur in the exploited areas where coal is exposed at surface (Illustration 14). They are generally very limited in extension and actively controlled by the mining company.

Illustration 14: coal fire at Jiží mine

4. Spectroradiometric measurements

4.1. INTRODUCTION

Two types of spectroradiometric measurements can be performed using the BRGM's ASD Fieldspec® 3 spectroradiometer:

- Field measurement in natural illumination conditions; this requires a sunny clear sky with low humidity to avoid too noisy spectra, in particular in the Short Wave Infrared (SWIR) range. This technique enables acquiring spectra over targets variable in size, according to the distance between the probe and the target (from few centimetres to several metres using for instance a cherry picker);

- Laboratory measurement in artificial illumination condition, using a specific probe: this type of measurement requires a physical contact between the target and the probe and is hence limited to the measurement of very small areas. It however avoids the signal perturbation by water absorption bands.

Due to the very bad weather condition that prevailed over central Europe during the first two weeks of September, it was nearly impossible to get field spectra, except on the very last afternoon at a single locality (the so-called Bohemian Geo Park)

4.2. COLLECTION OF SPECTRA FROM THE SOKOLOV BASIN STRATIGRAPHIC COLUMN MATERIAL

Petr Rojík (geologist at Sokolovsá Huhelná a.s.) provided his collection of representative samples of all the facies encountered in the Sokolov basin or stratigraphically equivalent (Cheb basin for instance, as described in Illustration 10. Three spectra from each sample have been collected, using the contact probe in artificial illumination (Illustration 15), in view of getting a reference spectral library of different facies of the regional material (see Appendix 1). Each sample was simultaneously photographed for record.

Illustration 15: acquisition of spectra from the Soklov stratigraphic column

A total of seventy different facies representative of the Sokolov Basin material and its surroundings was measured this way.

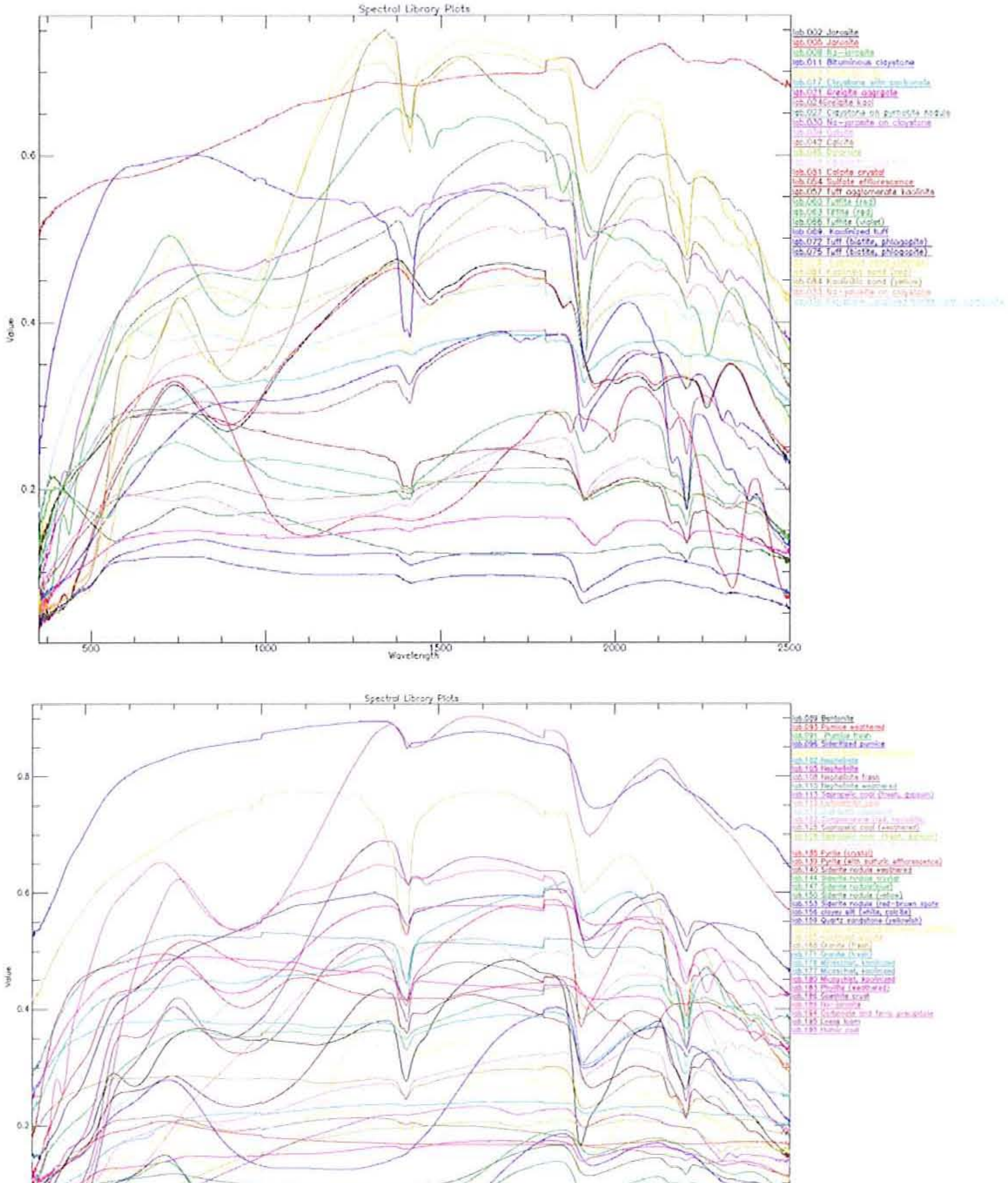

Illustration 16: Laboratory spectra of the Sokolov basin material

Spectra show distinctive absorption or reflection features typical of mineral or rock composition, such as goethite or hematite, jarosite…

These dedicated spectral libraries can be further used for image processing using different types of images (multispectral and hyperspectral). It is foreseen to complete them with more field spectroscopy measurements under better weather conditions in the coming years.

Spectra were further resampled to the ASTER spectral bands in view of proceeding to classification of the ASTER Images.

4.3. COLLECTION OF SPECTRA FROM FIELD SAMPLING

Due to the difficulty in collecting field spectra in natural illumination conditions, samples were collected in the field on several places for spectral measurements using the contact probe in artificial illumination. The CGS performed RX analyses over these samples.

The sample and measurement location are shown on Appendix 5, points MED (Medard mine), PV (Podkrušnohorská Výsypka dump site).

Corresponding spectral libraries have been built from these spectra.

4.4. SPECTRA MEASUREMENT IN NATURAL ILLUMINATION

It has been possible collecting few field spectra in natural illumination conditions during a sunny afternoon. About 15 spectra were collected around the Bohemian Geopark, representative of the different type of clays and rocks encountered there.

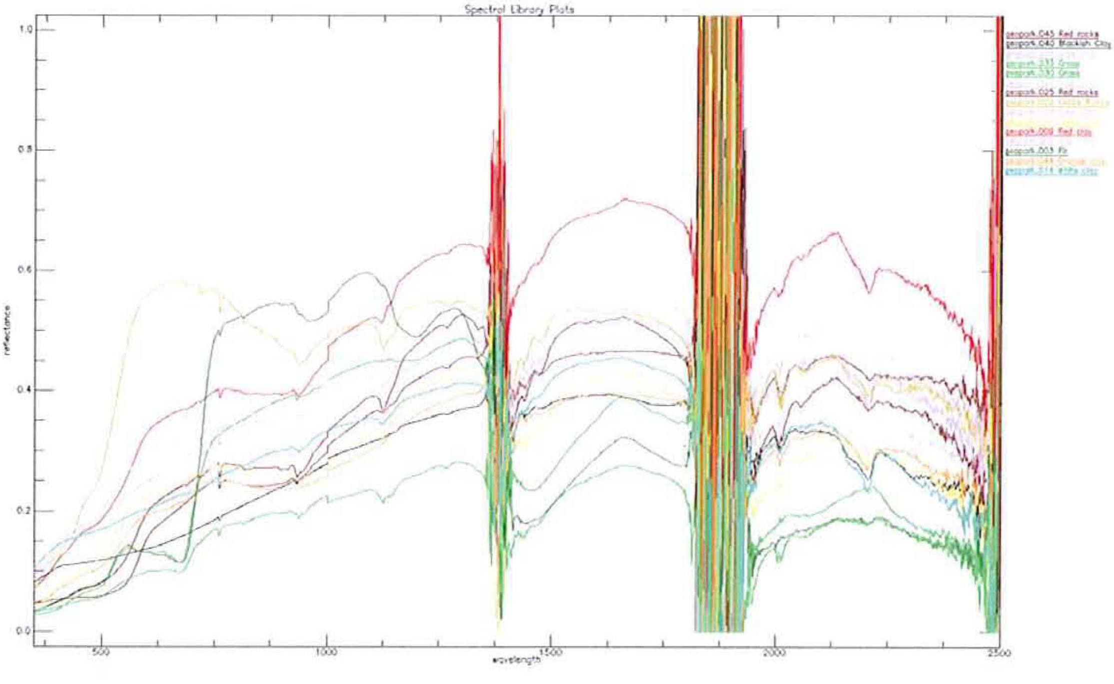

Illustration 17 : ASD field spectra collected at Bohemian Geopark.

The spectra are noisy in the SWIR 2 range (over 2350 nm in particular) due to humidity remaining in the air after rainy weeks. The spectral library built from these spectra was further resampled to the ASTER spectral bands in view of proceeding to classification of the ASTER Images.

5. Data processing

5.1. INTRODUCTION

The work carried out during this first phase of the project aimed at analyzing and identifying spectral features at the mining site. This was done using in situ and laboratory spectra of the Sokolov site field samples convolved to ASTER spectral resolution, focusing on the VNIR–SWIR spectral range.

X-ray powder diffraction (XRD) analysis was conducted on the field samples to supplement the mineralogical description of the samples measured in the field and in laboratory with ASD spectrometer. Currently 11 XRD analyses were supplemented with results; the rest of them will be finish by the end of 2007.

AMD mapping is based on the mapping of minerals that occur at the surface of waste-rock piles and their surrounding, focusing on minerals that serve as indicators of subaerial oxidation of pyrite ("hot spots") and the subsequent formation of AMD/ARD. natural leaching process of sulphur-rich material leads to the accumulation of Fe minerals, wherein centers of low-pH forming minerals, as copiapite and jarosite (pH< 3), are surrounded successively by goethite and hematite, minerals indicating progressive increase in pH (Illustration 18).

After atmospheric correction of the satellite imagery, the first step of the work consisted in building the spectral libraries representatives of jarosite, goethite, hematite and clay mineral groups (etc., endmembers) comprising field spectra, laboratory spectra from field samples and representative minerals from Sokolov site (collection of Dr. Rojík, Sokolovská uhelná a.s.) and well as selected mineral spectra from the USGS and JPL libraries.

5.2. ATMOSPHERIC CORRECTION OF THE ASTER IMAGERY

Available ASTER images have been corrected of atmospheric effects using the ATCOR 2 software. Conversion of data from radiance to reflectance makes possible the comparison of image spectra with reference spectral libraries, once the latter being resampled to ASTER spectral range and bands.

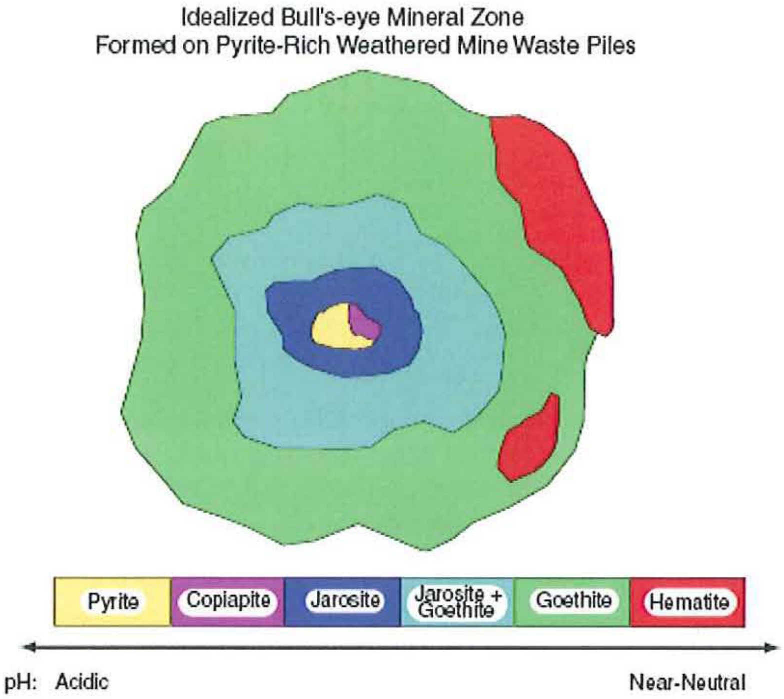

Illustration 18: Idealized bull's-eye pattern of spectrally detectable Fe-bearing secondary mineral zones.
Leachate pH is low and metal leachability high in the central pyrite, copiapite, and jarosite spectral mineral zones, while leachate pH is high and metal leachability

5.3. SPECTRAL CHARACTERISTICS OF THE SELECTED ENDMEMBERS

Before being used for further image processing, continuous spectra (2500 measurements at 1 nm spacing with ASD FieldSpec® 3), must be resampled to the spectral intervals and spectral bands of the image data set, i.e. nine spectral bands in the VNIR and SWIR range for ASTER. Illustration 22 shows a kaolinite spectrum from the USGS mineral spectral library (black curve) resampled to ASTER spectral bands (purple curve).

5.3.1. Iron oxy-hydroxides

Illustration 19 displays USGS mineral spectra library goethite and hematite spectra resampled to ASTER spectral bands, together with goethite or hematite rich material spectra from the Sokolov basin (named as lab.[spectrum number].[material name]).

Despite resampling to ASTER bands, iron oxy-hydroxides spectra still show diagnostic absorption at the wavelength of 0.8 µm (ASTER band 3), more visible on the hematite group minerals, while goethite mineral show distinctive reflection feature at the 0.661 µm wavelength (ASTER band 2).

These spectral features are confirmed on iron oxy-hydroxide rich material from the Sokolov basin. The absorption feature at the 2.209 µm wavelength (ASTER band 6) indicates the presence of clay minerals in these materials. Indeed, geological material represent almost always intimate mixtures of different minerals and clay minerals may be found in the mixture material most frequently encountered at the Sokolov site

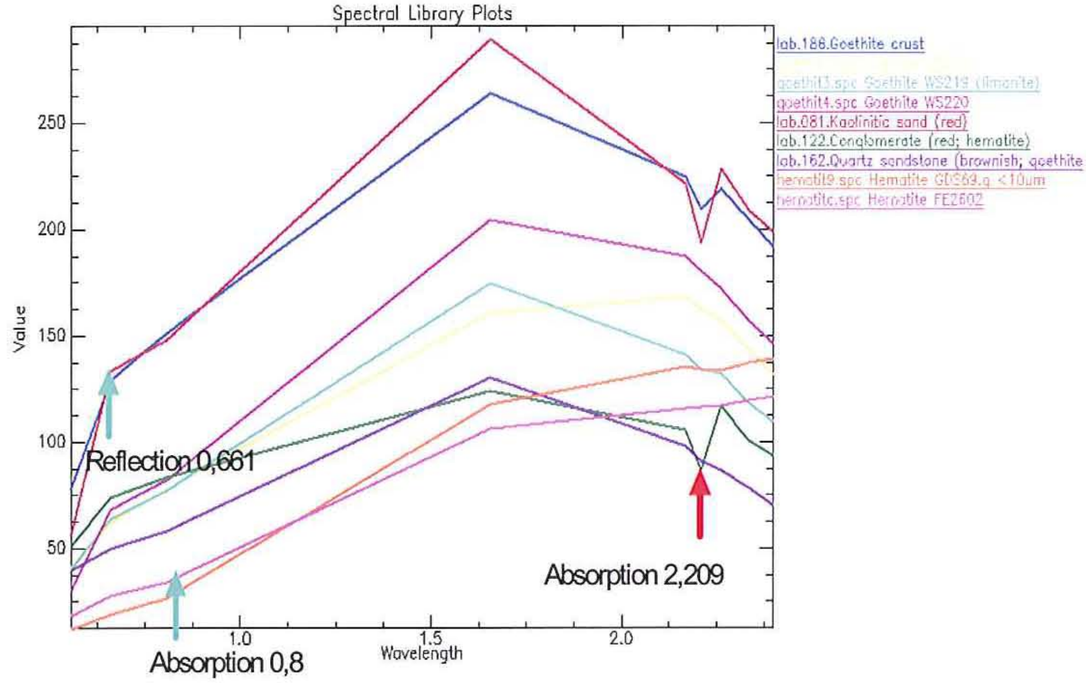

Illustration 19: Spectral library for iron oxy-hydroxides comprised of spectral properties of the representative minerals of Sokolov site (lab.) and USGS mineral library (resampled to Aster spectral resolution)*

5.3.2. Jarosite mineral group

Illustration 20 displays USGS mineral spectra library Jarosite, Na-Jarosite and ammonio-jarosite spectra resampled to ASTER spectral bands, together with jarosite and Na-jarosite spectra from the Sokolov basin (named as lab.xxx spectra).

Despite resampling to ASTER bands, jarosite and associated mineral spectra still show diagnostic absorption at the wavelength of 0.8 µm (ASTER band 3), similar in this to iron oxy-hydroxydes, but also a supplementary typical absorption feature at 2.167 µm (ASTER band 5)

These spectral features are confirmed on jarosite and Na-jarosite material from the Sokolov basin. The absorption feature at 2.262 µm (ASTER band 7) indicates the presence of clay minerals in these materials, which confirms the mixture material type found in the basin (Illustration 22).

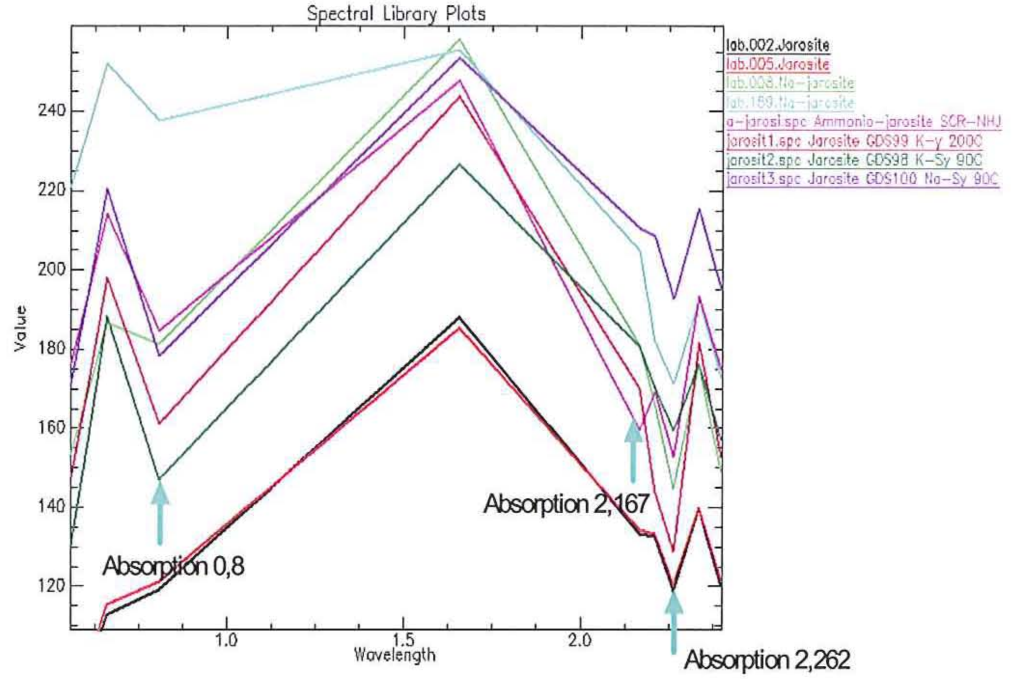

Illustration 20: Spectral library for jarosite comprised of spectral properties of the representative minerals of Sokolov site (lab.) and USGS mineral library (resampled to Aster spectral resolution).*

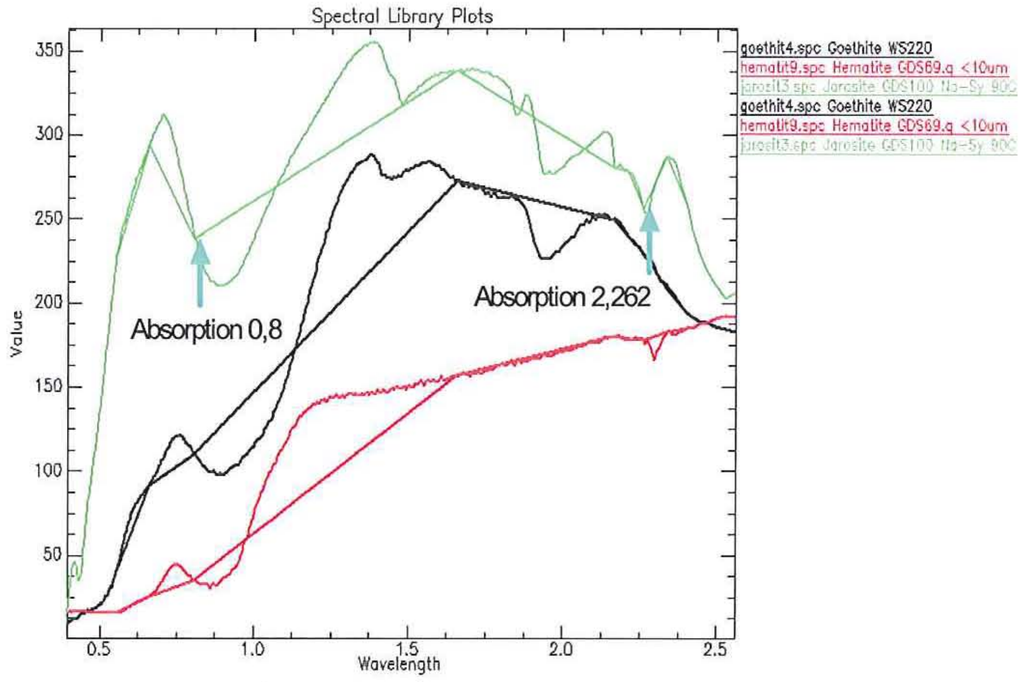

Illustration 21: Spectral library for iron oxy-hydroxides and jarosite – comparison between full reflectance spectral curves and resampled to ASTER spectral curves.

5.3.3. Clay minerals

Clays are the most common minerals at the open pit mine site, and thus can be found in different geological materials as a part of the intimate mixture. They present a strong distinctive absorption feature near to 2.209 µm, i.e. ASTER band 6 (Illustration 22). Our study confirmed that finding as the clay absorption feature was found at 2.209 µm (Illustration 22).

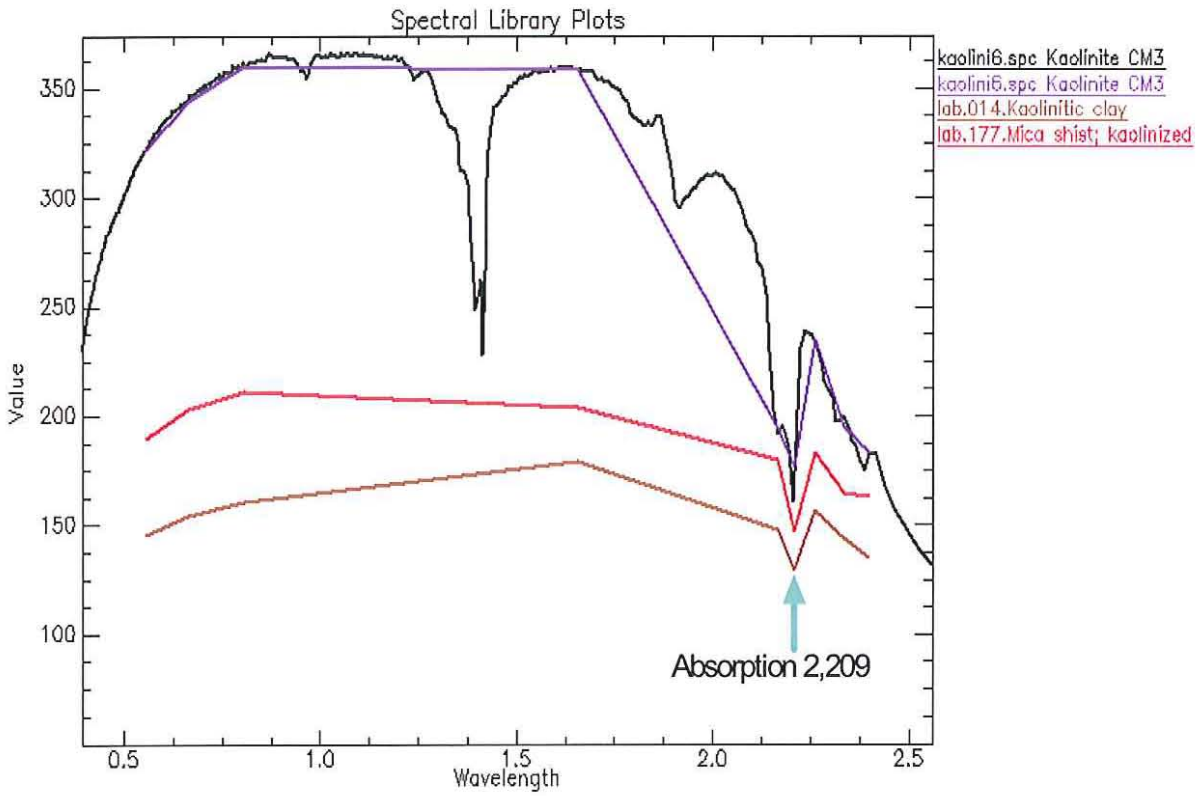

Illustration 22: Spectral library for clay minerals comprised of spectral properties of the representative minerals of Sokolov site (lab.) and USGS mineral library (the full reflectance spectral curve in comparison with the resampled ones).*

5.3.4. Summary of spectral identification features available from ASTER bands

Clays can be identified by absorption features on ASTER band 6 and to a lower extent band 7.

Iron oxy-hydroxides can be identified by absorption feature on ASTER band 3 and reflection on band 2.

Jarosite an Na-jarosite can be identified by strong absorption feature on ASTER band 5 and minor absorption on band 3.

5.4. ENDMEMBERS FROM ASTER IMAGE

Endmembers from the pre-processed (atmospherically corrected with Atcor SW) Aster image (12/9/2004) were extracted via applying the Sequential Maximum Angle Convex Cone method (SMACC). Spectra of the extracted endmembers were compared with the spectra from the field, field samples and mineral libraries and then associated with the spectral features of the indicative mineral groups. Illustration 23 shows that endmembers 4 and 9 can be associated with the vegetation showing the typical NIR (0.801 µm) /Red (0.661 µm) bands behavior. Endmembers 3, 5, 6, 8 due to the reflection in 1.7 µm wavelengh and absorption before 2.2 µm (ASTER band 5) depict jarosite abundance. The absorption in 2.262 (ASTER band 7) and 2.34 (ASTER band 8) prove clay mineral abundance. The absorption at 0.801µm, typical for iron oxy-hydroxides, was not found on the endmember spectral curves. This might be due to vegetation interference with iron oxy-hydroxide spectral features in that particular spectral band

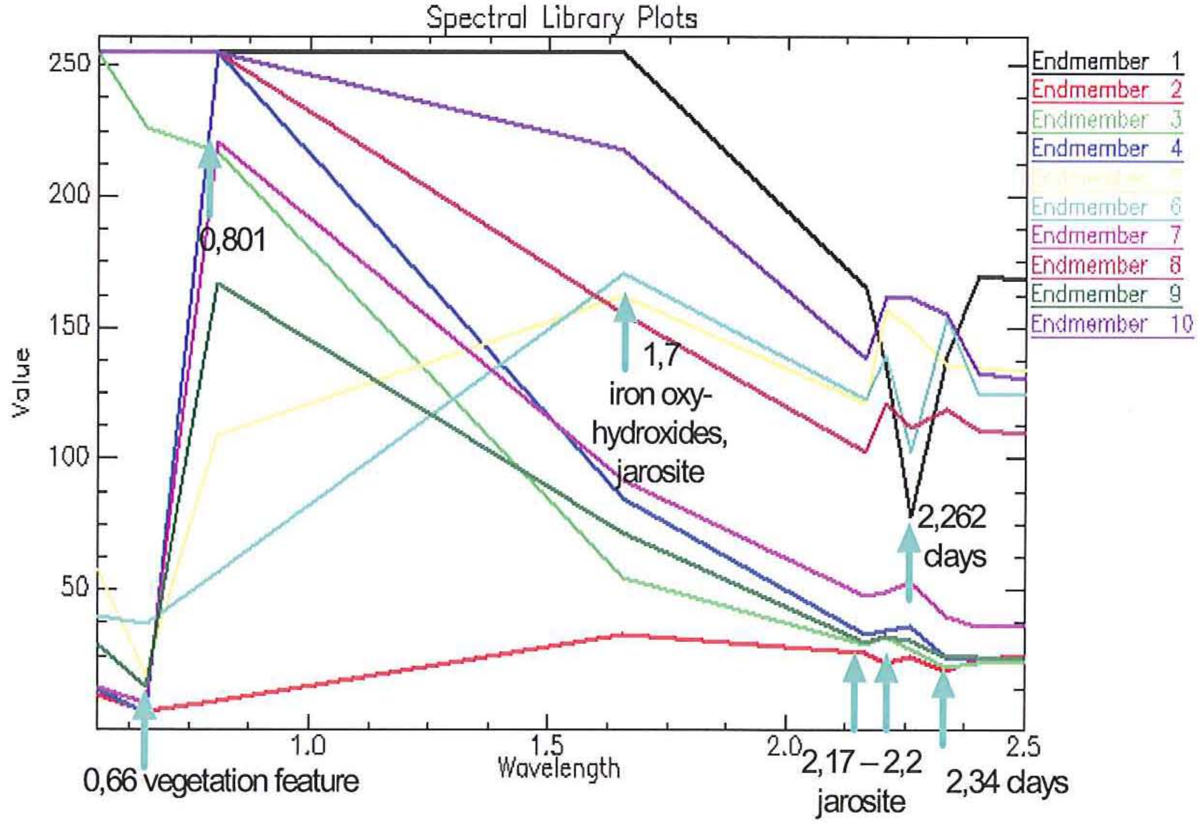

Illustration 23: Extracted endmember spectral library and associated diagnostic features of the indicative minerals.

5.5. ASTER IMAGE CLASSIFICATIONS BASED ON ENDMEMBER SPECTRAL PROPERTIES

The Spectral Analyst is used to help identify materials based on their spectral characteristics. The Spectral Analyst uses ENVI techniques such as Spectral Angle Mapper (SAM), and Spectral Feature Fitting (SFF) to rank the match of an unknown spectrum to the materials in a spectral library. The output of the Spectral Analyst is a list of the materials in the input spectral library ranked in order of best-to-worst match. An overall similarity score is reported, along with individual 0 to 1 scores for each method. Illustration 24 shows the results for 10 endmembers extracted from the ASTER image.

Endmembers	Hematite SAM/SFF	Goethite SAM/SFF	Jarosite SAM/SFF	Clay SAM/SFF
1	0.71/0.67	0.73/0.70	0.74/0.78	0.74/0.71
2	0.74/0.78	0.65/0.66	0.67/0.65	0.65/0.61
3	0.68/0.60	0.71/0.63	0.72/0.70	0.73/0.67
5	0.67/0.65	0.66/0.62	0.64/0.62	0.64/0,62
6	0.83/0.79	0.81/0.76	0.86/0.85	0.80/0.76
7	0.58/0.56	0.57/0.54	0.55/0.53	0.57/0.54
8	0.87/0.86	0.89/0.89	0.91/0.91	0.90/0.86
9	0.60/0.56.	0.60/0.540	0.60/0.56	0.60/0.56
10	0.90/0.91	0.92/0.91	0.92/0.92	0.93/0.93

Illustration 24: Two spectral analysis techniques were employed to identify the endmembers from ASTER: Spectral Angel Mapper (SAM)/Spectral feature fitting (SFF)

5.5.1. ASTER Image classification employing the Linear Spectral Unmixing model

Linear Spectral Unimixing (LSU) allows determining relative abundance of materials depicted in multispectral/hyperspectral imagery based on the materials' spectral characteristics. The reflectance at each pixel of the image is assumed to be a linear combination of the reflectance of each material (or endmember) present within the pixel (Settle and Drake, 1993).

Spectral reflectance curves measured from the representative mineral samples of Sokolovská open pit mine were used as input endmembers, i.e. jarosite, goethite and clay minerals.

The clay – jarosite - goethite "ternary map" displayed in Illustration 25 depicts the presence of AMD related minerals and their mixture with clay minerals

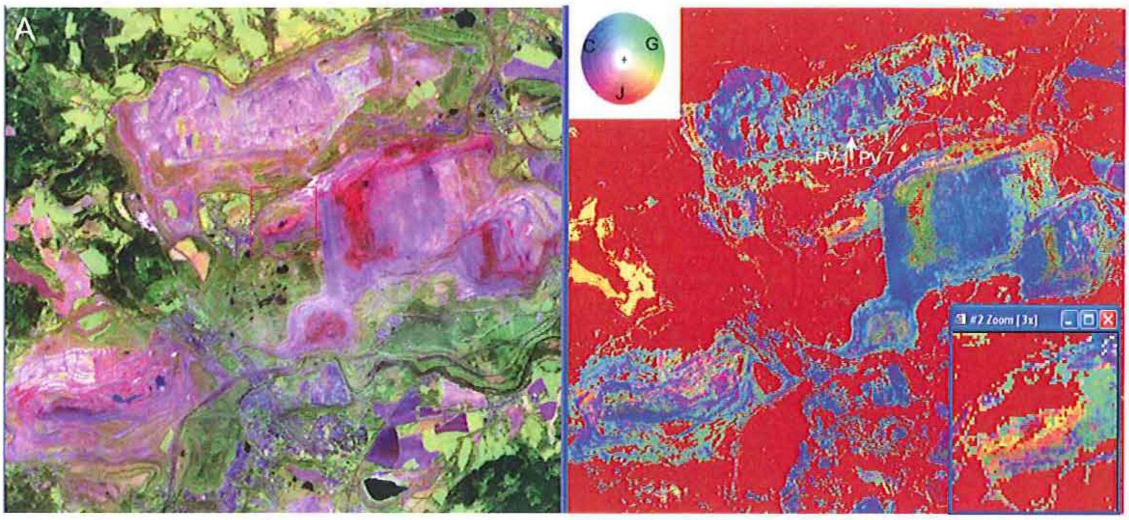

Illustration 25 : Clay – jarosite - goethite "ternary map" using LSU algorihm. (C = clay, J = jarosite, G = (goethite).
"No data" value in dark red. PV 1 and PV 7 represent the locations where occurrence of jarosite was proven by XRD analyses

5.5.2. ASTER Image classification employing the Match Filtering model

Match Filtering method employs a partial unmixing model to find the abundance of user-defined endmembers (Harsanyi and Chang, 1994). This technique maximizes the response of the known endmember and suppresses the response of the composite unknown background, thus matching the known signature. It provides a rapid means of detecting specific materials based on matches to library or image endmember. In this particular case the endmemeber spectra were extracted applying the Sequential Maximum Angle Convex Cone method (SMACC) to ASTER image (see 5.4) and used as input endmembers to a MF mapping model.

Spectral Analyst, the spectral statistical tool of ENVI, helped to identify the materials of ASTER-based endmembers in which case each pixel spatially defined by 30x30 m in SWIR spectral region represents rather material mixture than a pure material pixel (Illustration 24). Higher scores indicate higher confidence because of better match. Greater separation between adjacent scores indicates higher confidence in the similarity. In Sokolov case, the scores from one mineral follow pretty much the scores for other ones, considering individual endmembers. This indicates, that endmembers still represent mixture materials and further investigation should lead to (a) a better discrimination of pure pixels, (b) selection of a different wavelength range or (c) use the different weighted methods.

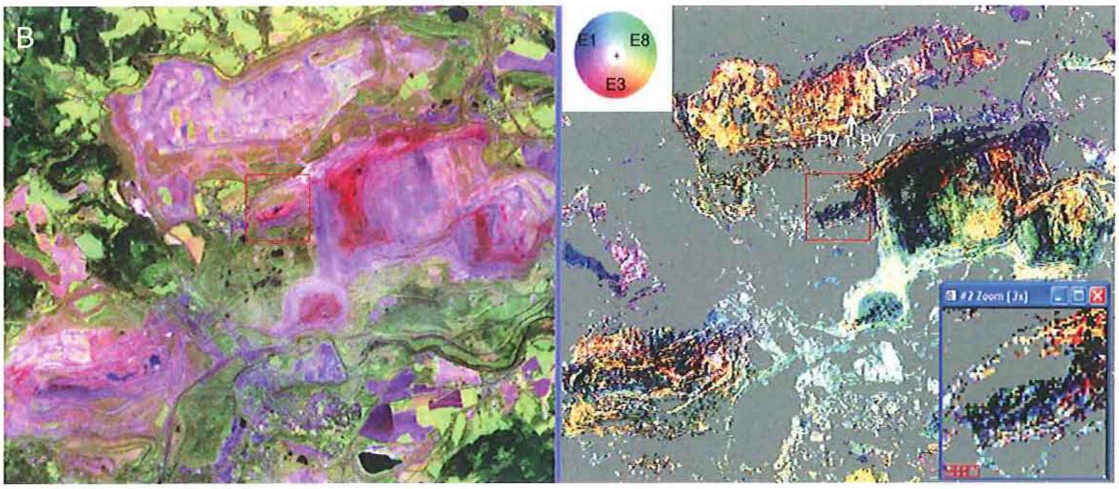

Illustration 26: Results of classification employing MF algorithm
E1 = Endmember 1 (majority of clay minerals, jarosite and goethite), E8 = Endmember 8 (purest pixel – highest abundance of jarosite and clay minerals), E3 = Endmember 3 (lower abundance of clay mineral and jarosite

5.6. SPECTRAL ANGLE MAPPER CLASSIFICATION FROM FIELD SPECTRA

A Spectral Angle Mapper (SAM) classification procedure was applied to the ASTER image using the field spectra measure at GeoPark.

Appendix 8 shows an accurate classification of Cypris clays ("gray clays" and "red clays") over the mining areas (open pits and dumps).

"Yellow clays" and "yellow rocks" (jarosite coating) are found in several places in the open pits and dumps, which tends to reflect field observation, despite it remains to be further checked location by location.

5.7. ATTEMPT FOR MAPPING POTENTIAL WATER CONTAMINATION

Image spectra corresponding to various water types were collected: surface water, turbid water, contaminated water at Geopark and contaminated water (red waters) at Medar pit. A SAM classification algorithm was applied to the Visible and Near infrared bands of the ASTER image (below 1µm). The result, presented in appendix 9, clearly shows turbid waters in former open pits (South and South East of Sokolov, contaminated waters in several pits West of Sokolov, including Medard pit and South of Habartov. Highly contaminated water is found South of Hor Pochlovice. However, contaminated like waters are classified out of the mining area.

6. Conclusions

Even though being at its early stage, this study confirms that digital spectral processing of satellite imagery backed by field spectroscopy and field sample spectroscopy represents an invaluable technique in mapping minerals and in particular mineral species related to AMD in mining areas, despite the relatively weak number of spectral bands of the ASTER sensor.

First results comparing the mineral maps derived from ASTER imagery to field samples backed with XRD analyses demonstrated the ability of spectral remote sensing in mapping mineral species such as secondary iron minerals. Image processing identified jarosite as a part of the mixture material in the Sokolov mining area in accordance with the performed XRD analyses. However further investigations leading to more accurate qualitative and quantitative analyses remain necessary. Hyperspectral data such as HYPERION and/or airborne data are suggested to improve spectral resolution with respect to ASTER data.

Further testing of different mineral mapping techniques applied to multi-sensor satellite imageries (ASTER, HYPERION airborne sensors) focusing on "pure pixel" definition and subsequent implementation of sub-pixel abundance processing algorithms such as Spectral Hourglass procedure and Mixture Tuned Matched Filtering (MTMF) would be worth to do. Additional field campaign is also requested in order to collect more in-situ spectroradiometic measurements and more samples for XRD analyses to validate the mineralogical contents and to support mineral mapping techniques. Furthermore, the Czech Geological Survey recently purchased a new portable X-ray fluorescence spectrometer. Detailed investigation of pH-dependent equilibrium between spectrally detectable minerals and heavy metals mobilization/imobilization will be made possible using this field investigation technique.

Eventually, possible correlation between water classification and presence of sulfates as mapped from ASTER image classifications is to be checked and validated.

7. References

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Murad, E., and Rojík, P., (2003) Iron-rich precipitates in a mine drainage environment: Influence of pH on mineralogy, *American Mineralogist.*2003; 88: 1915-1918

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Harsanyi, J. C. and Chang, C., I. (1994): Hyperspectral image classification and dimensionality reduction: an orthogonal subspace projection approach. IEEE Transections on Geoscience and Remote Sensing, 32, 779-785.

Settle, J., J. and Drake, N., A. (1993): Linear mixing and the estimation of ground cover proportions. International Journal of Remote Sensing, 14, 1159-1177.

Appendix 1: samples from the Sokolov stratigraphic column

Spectra Nr.	Name (brief petrographic/mineralogic characteristics)	Stratigraphic level (age)	Location (SB = Sokolov Basin)	Photo Nr.
lab 5-7	Jarosite	Holocene	Cheb Basin – Soos	31
lab 8-10	Na-jarosite	Recent antropogenic	SB – Coal mine Jiří – entrance to the adit 32Ha	31
lab 11-13	Bituminous claystone	Cypris Form.- correlation layer 42[1]	SB – Coal mine Marie	32
lab 14-16	Kaolinitic clay (ball clay)	Cypris Form.- correlation layer 36	SB – Coal mine Družba	33
lab 17-19	Claystone with carbonate? and calcified fossiles	Cypris Form.-upper part	SB – Coal mine Družba	34
lab 21-23	Greigite aggregate on kaolinitic claystone (face side)	Cypris Form.-middle part-corr.layer 54	SB-Coal mine Družba	35
lab 24-26	Greigite on kaolinitic claystone (reverse site)	dtto	dtto	36
lab 27-29	Claystone on the pyrhotite nodule	Cypris F.-middle part	SB-Coal mine Družba	37
lab 30-32	Na-jarosite on claystone	Cypris F.-middle part.-close to corr. layer 38	SB-coal mine Jiří	38
lab 33-35	Na-jarosite on claystone	dtto	dtto	39
lab 36-38	Claystone (argillized tuffite), with carbonates and analcite?	Cypris F.-upper part	SB-coal mine Družba- drill Dp 246, depth 10,7 m	40
lab 39-44	Carbonate (calcite) (karbonatized clay), side without cristals	Cypris F.-middle part-corr.layer 49	SB-intersection of coal mines Jiří and Marie	41,42
lab 45-47	Carbonate (dolomite) (carbonatized clay)	Cypris F.-middle part-corr.layer 51	SB-coal mine Marie	43
lab 48-50	dtto lab 45-47 grid	dtto	dtto	44
lab 51-53	Carbonate (calcite), sample dtto lab 39-44, side with calcite cristals	Cypris F.-middle part-corr.layer 49	SB-intersection of coal mines Jiří and Marie	45
lab 54-56	Efflorescence of thénardite and/or gypsum	Recent dump	Dump Podkrušnohorská výsypka	46
lab 57-59	Tuff agglomerate	Chodov Member-close to layer 21	SB-Coal mine Jiří	47
lab 60-65	Tuffite (red)	Chodov Member-corr.layer 23	SB-coal mine Jiří	49

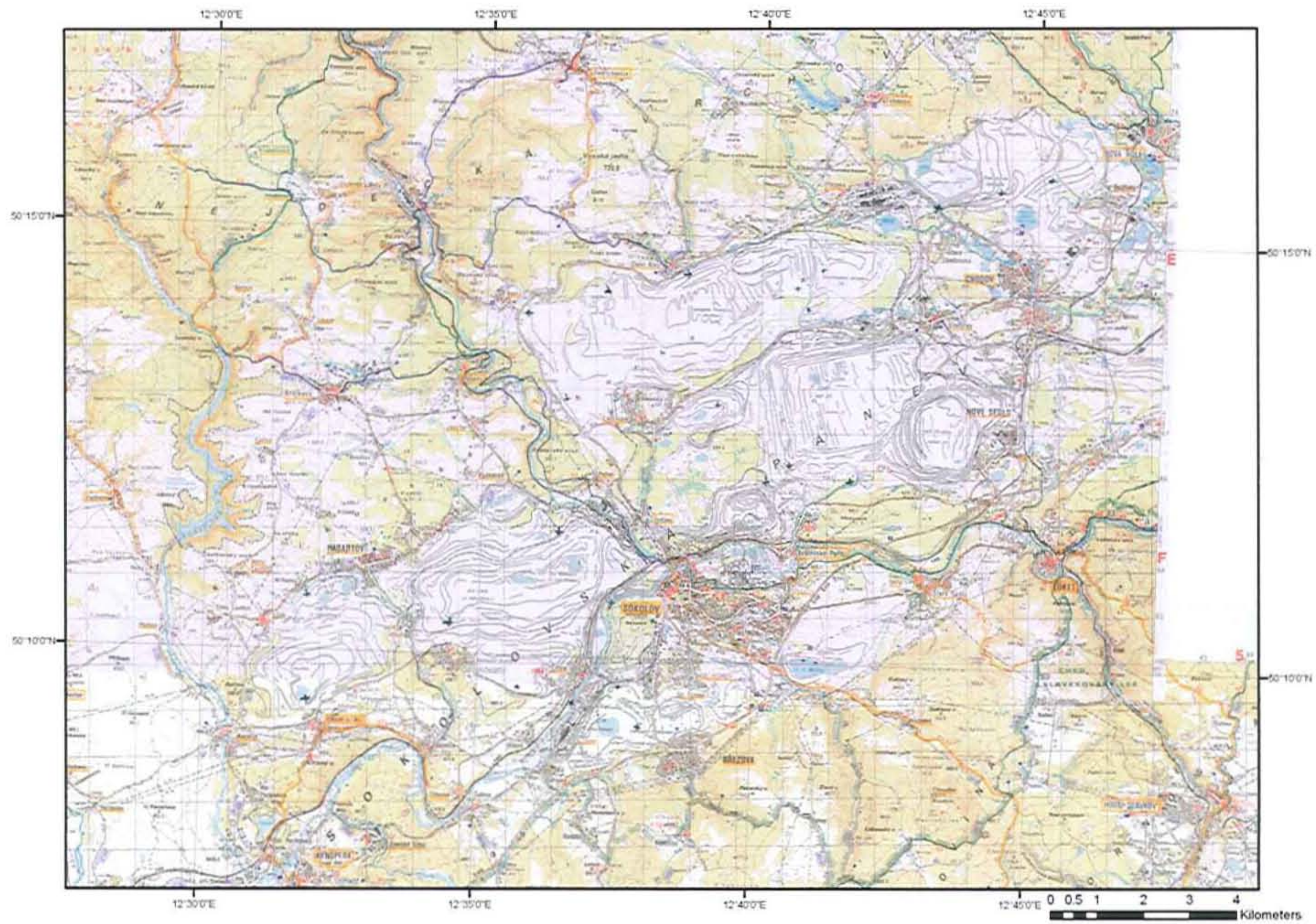
[1] "Corr. Layer" refers to layer number in Illustration 10

lab 66-68	Tuffite (violette)	Chodov Member-corr.layer 23	SB-intersection of coal mines Jiří and Lomnice	49
lab 69-71	Kaolinized lapilli tuff	Chodov Member	SB-coal mine Medard	50
lab 72-74	Tephritic tuff with fenocrists of biotite or phlogopite	Doupovské hory Mts. strato-volcano (here equivalent of Chodov M.)	Doupovské hory Mts.-Vojkovická stěna	51
lab 75-77	Tephrite tuff with phenocrists of biotite or phlogopite (detail-mica)	dtto	dtto	51
lab 78-80	Kaolinitic quartz sand coloured with goethite and haematite – orange spot	Chodov Member-bottom part-corr.layer 16	SB-Karlovy Vary-Dvory	52
lab 81-82	dtto – red spot	dtto	dtto	52
lab 83-86	dtto – yellow spot	dtto	dtto	52
lab 87-89	Bentonite	Chodov M.-corr. layer 21	SB-coal mine Družba	53
lab 90-92	Pumice (originally trachyte composition), fresh side	Chodov M.-corr.layer 21	SB-coal mine Družba	54
lab 93-95	Pumice (originally trachyte composition), slightly wheathered side	dtto	dtto	55
lab 96-98	Strongly sideritized pumice (originally bazaltic composition)	Chodov Member, between corr.layers 21 and 22	SB-coal mine Družba	56
lab 99-101	Argillized and carbonatized lapilli tuff	Těšovice Member	SB-coal mine Družba	57
lab 102-104	Olivinic nephelinite, quarried	Tertiary	Krušné hory Mts.-quarry between Rotava and Jindřichovice	58
lab 105-107	Olivinic nephelinite, quarried	Chodov Member	SB-quarry Dasnice	59
lab. 108-109	dtto more fresh	dtto	dtto	59
lab 110-113	Olivinic nephelinite wheathered close to the earth surface	Chodov Member	SB-Dasnice quarry	60
lab 114-115	Sapropelic coal	Josef Member	SB-coal mine Medard	61
lab 116-118	Liptodetritic coal	Josef Member	Tepelská vrchovina Mts.-Dražov	62
lab 119-121	Sapropelic claystone	Josef Member	SB-coal mine Družba	63
lab 122-124	Konglomerate – red spots	Davidov Member	SB-Bukovany	64
lab 125-127	Sapropelic coal, weathered	Josef Member	SB-Spoil dump Podkrušnohorská výsypka	65
lab 128-130	Sapropelic coal, weathered, with gypsum, relatively fresh surface	Josef Member	SB-Spoil dump Podkrušnohorská výsypka	65
lab 131-	Pyrite nodule, weathered,	Josef Member	SB-Spoil dump Podkrušno-	66

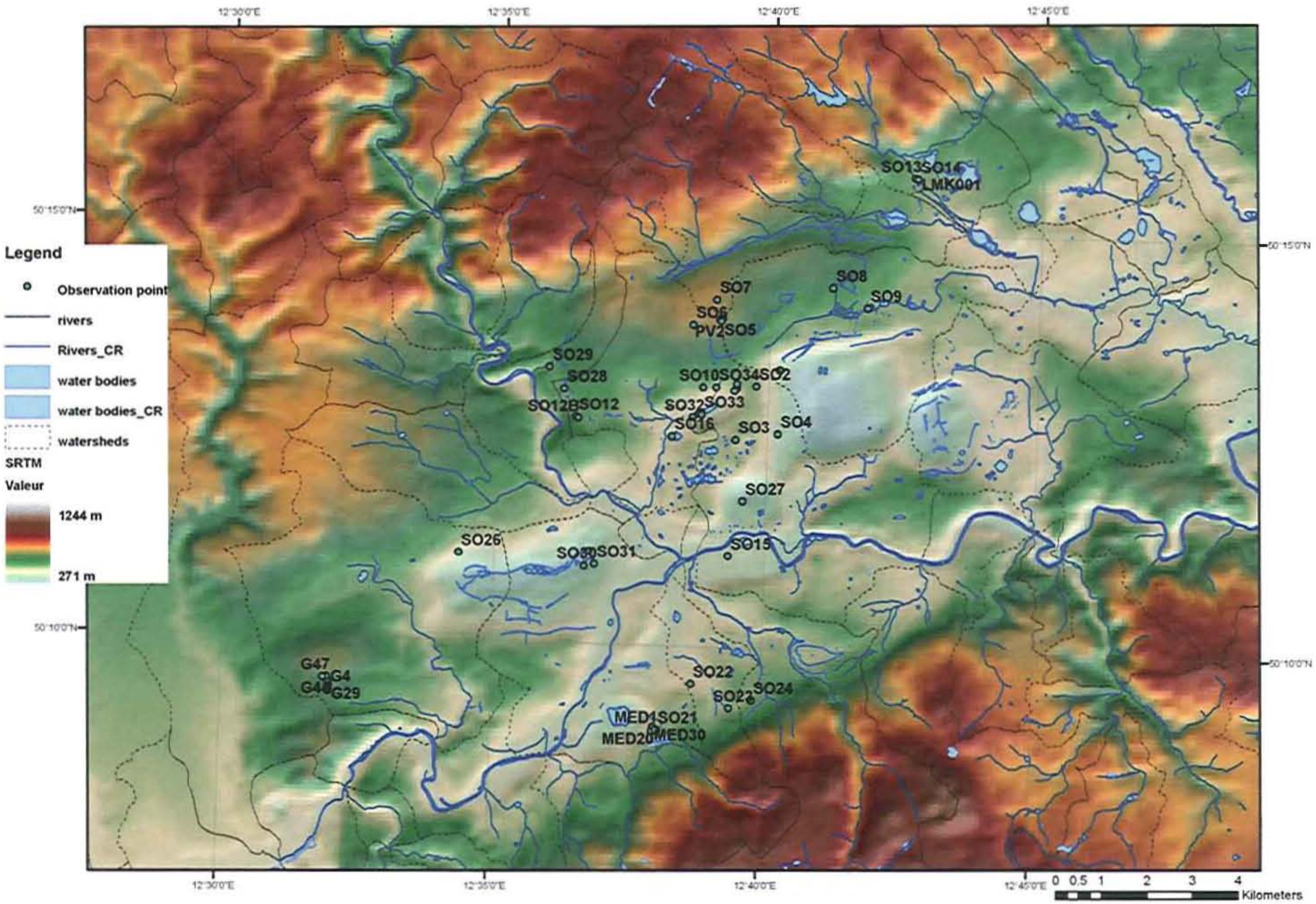
132	ochre surface		horská výsypka	
lab 133-136	Pyrite nodule, weathered	Josef Member	SB-Spoil dump Podkrušno-horská výsypka	67
lab 137-139	Pyrite nodule, weathered, white sulfuric efflorescence	Josef Member	SB-Spoil dump Podkrušno-horská výsypka	67
lab 140-142	Siderite nodule, wheathered	Chodov Member	SB-Spoil dump Podkrušno-horská výsypka	68
lab 144-146	Siderite nodule	Antonín Member (base)	SB-Lomnice coal mine	69
lab 147-149	Siderite nodule – blue spot	Antonín Member (base)	SB-Jiří coal mine	70
lab 150-152	dtto - yellowish spots	dtto	dtto	70
lab 153-155	dtto- red-brown spots	dtto	dtto	71
lab 156-158	Clayey silt (white)	Staré Sedlo Fm.	SB-sand pit Erika	72
lab 159-161	Quartz sandstone fine-grained yellowish	Staré Sedlo Fm.	SB-sand pit Erika	73
lab 162-164	Quartz sandstone coarse-grained, brownish, with goethite cement	Staré Sedlo Fm.	SB-sand pit Erika	74
lab 165-167	Kaolin (strongly kaolinized granite)	granite basement	SB-coal mine Družba	75
lab 168-173	biotite-granite, fresh	granite basement	Slavkovský les Mts.-quarry Vítkov	76
lab 174-176	mica shist to gneiss musco-vite-biotitic, kaolinized	cristalline basement	SB-coal mine Medard, bore-hole Či 101, depth 84,5 m	77
lab 177-182	mica shist garnet- musco-vitic, strongly kaolinized	cristalline basement	SB-coal mine Medard, bore-hole Sv 55	78
lab 183-185	phyllite, slightly weathered	Krušné hory Mts.	Kraslice	79
lab 186-188	goethite crust	recent precipitate from mine drainage water	SB-Lomnice-abandoned little coal mine Jiří	80
lab 189-191	Na-jarosite	recent precipitate along the Sokolov Fault	SB-Coal mine Družba	81
lab 192-194	carbonate and ferric precipi-tate	recent precipitate from cleaning plant of mine drain-age waters	SB-Cleaning plant Medard at Svatava	82
lab 195-197	loess loam	Pleistocene	SB-coal mine Silvestr	83
lab 198-200	Humic coal, dull	Anežka Member	SB-coal mine Medard – sec-tion M 10	84
lab 201-203	Sapropelic coal – black, brittle spot	Anežka member-	SB-coal mine Medard – sec-tion M 10	85
lab 204-206	Coal – brown spot	dtto	dtto	85
lab 207-209	Liptodetritic coal with bright xylitic roots – light brown liptodetritic surface	Antonín Member	SB-coal mine Medard-Libík	86

lab 210-212	dtto - dark brown xylitic surface	dtto	dtto	87
lab 214-215	Xylitic coal, wheathered	Antonín Member	SB-coal mine Silvestr	88

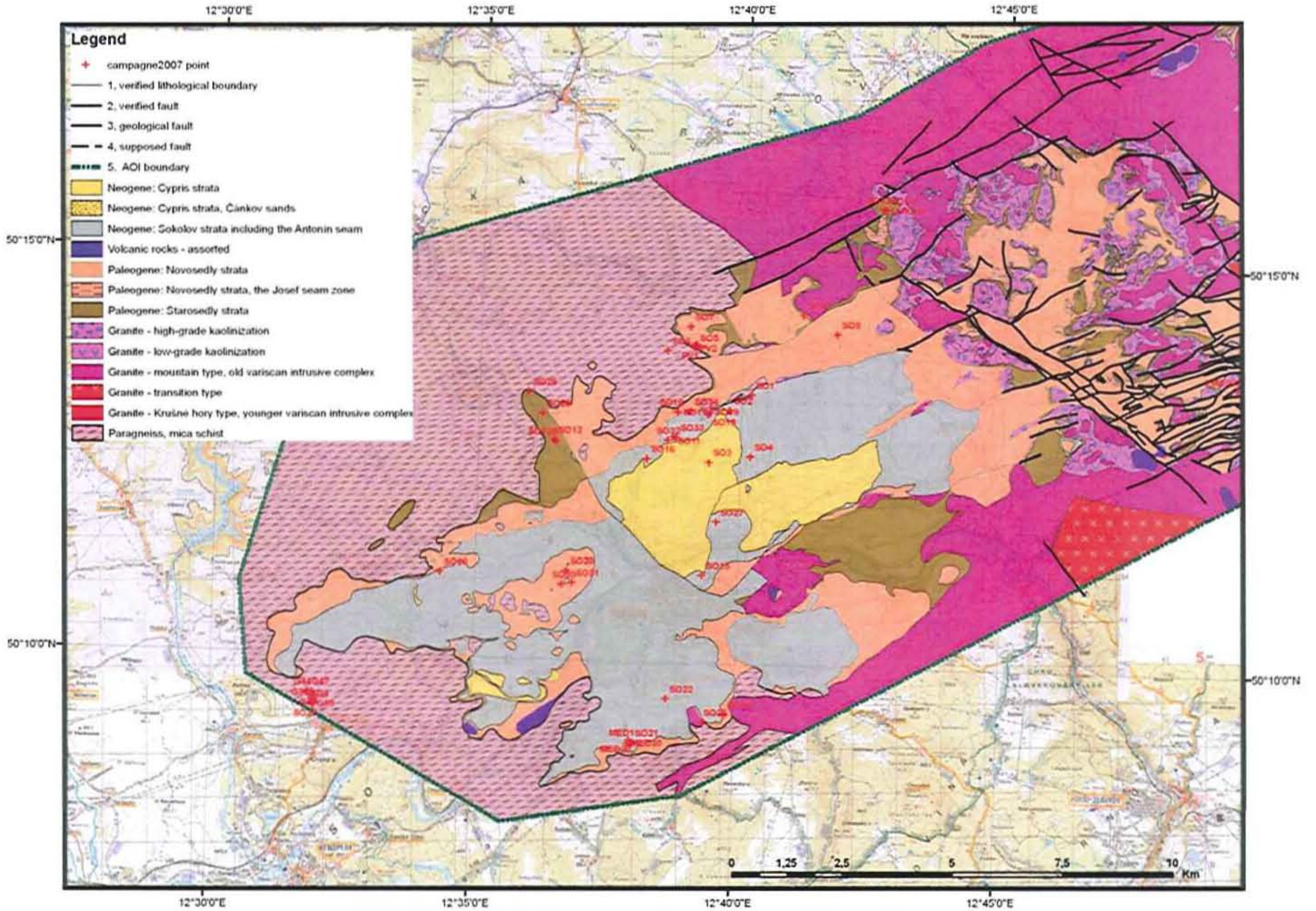
Appendix 2: Topographic maps



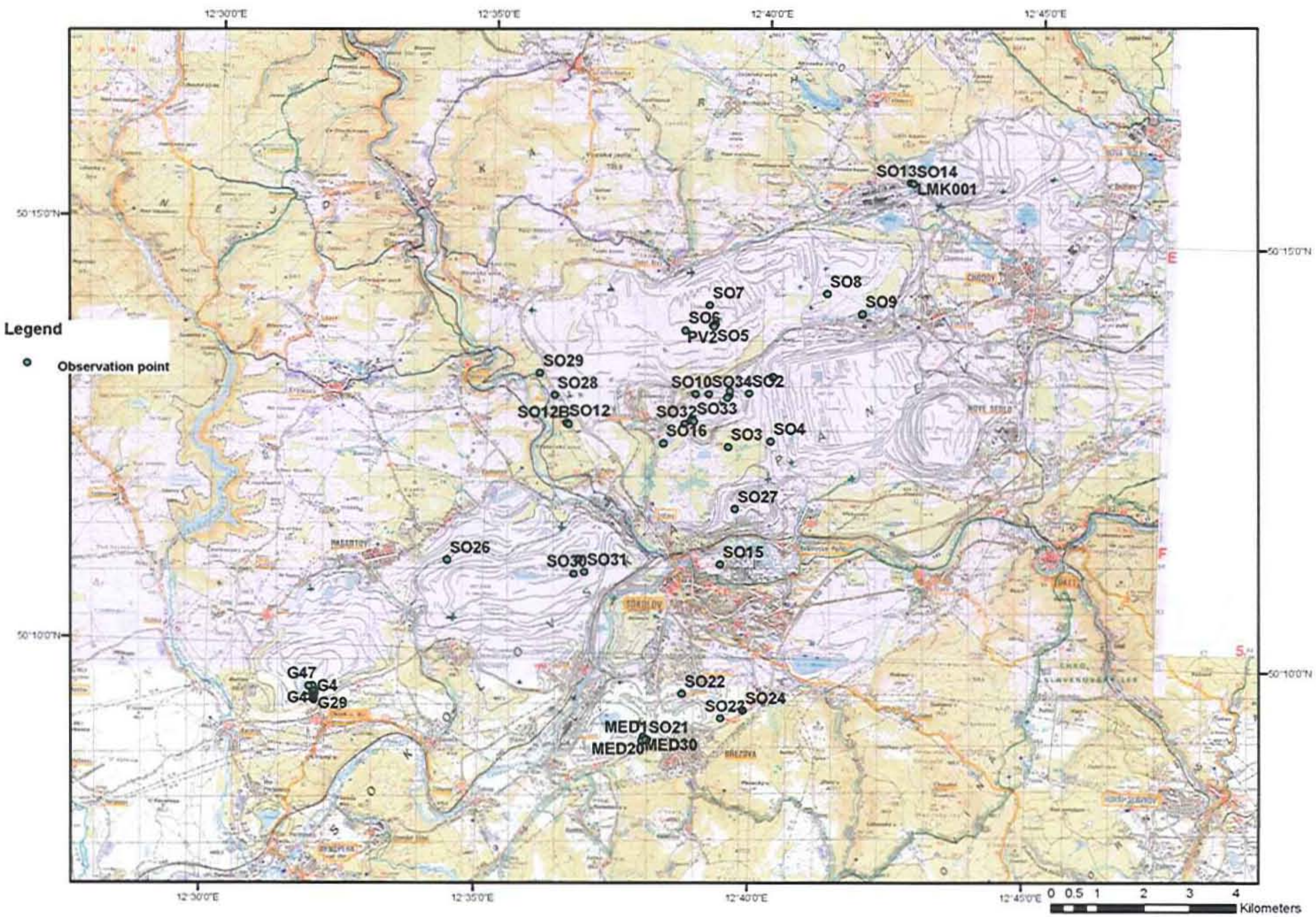
Appendix 3 : Digital Elevation Model SRTM



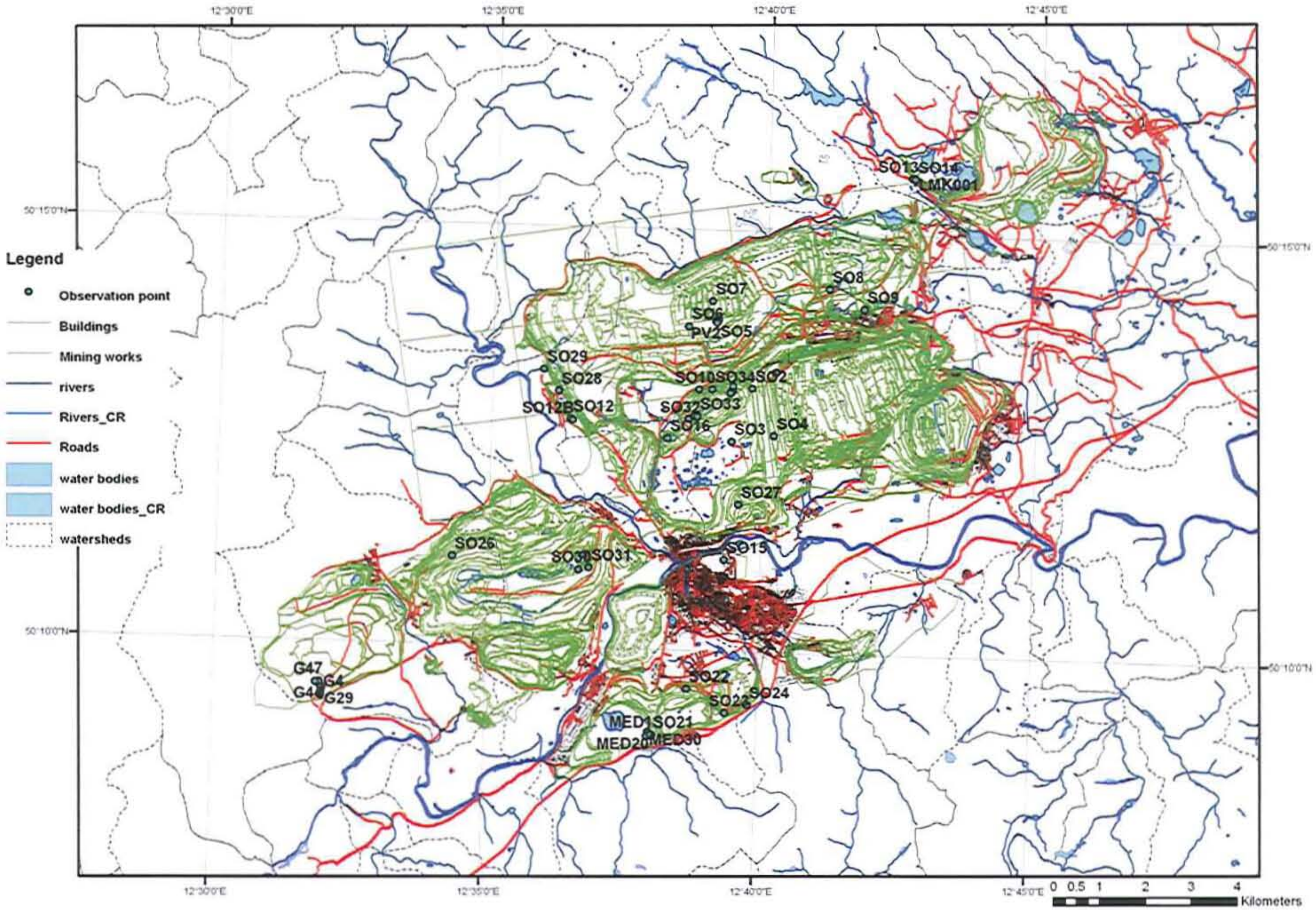
Appendix 4 : Geological map of the Sokolov Basin



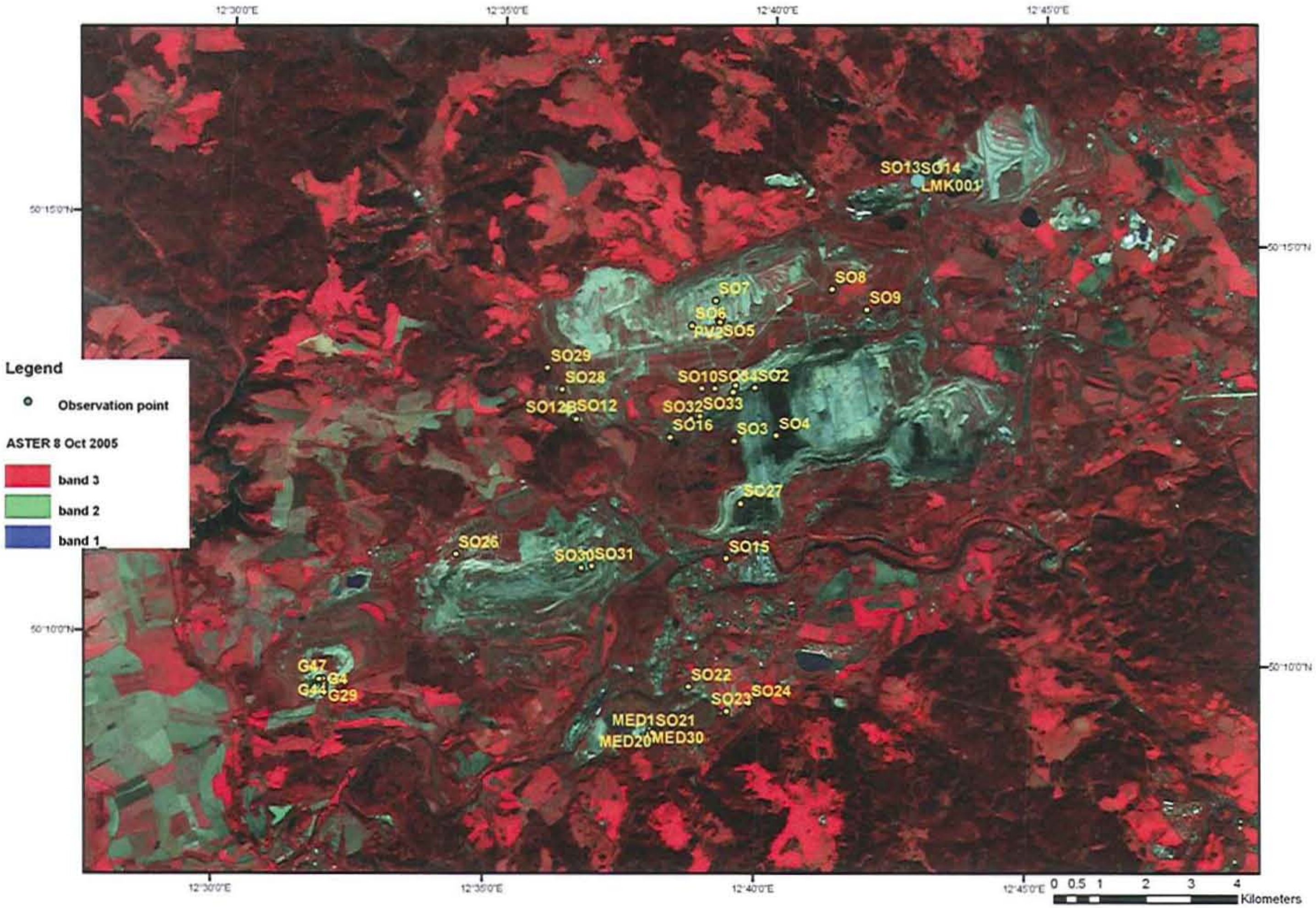
Appendix 5 : Field observation and/or measurement points



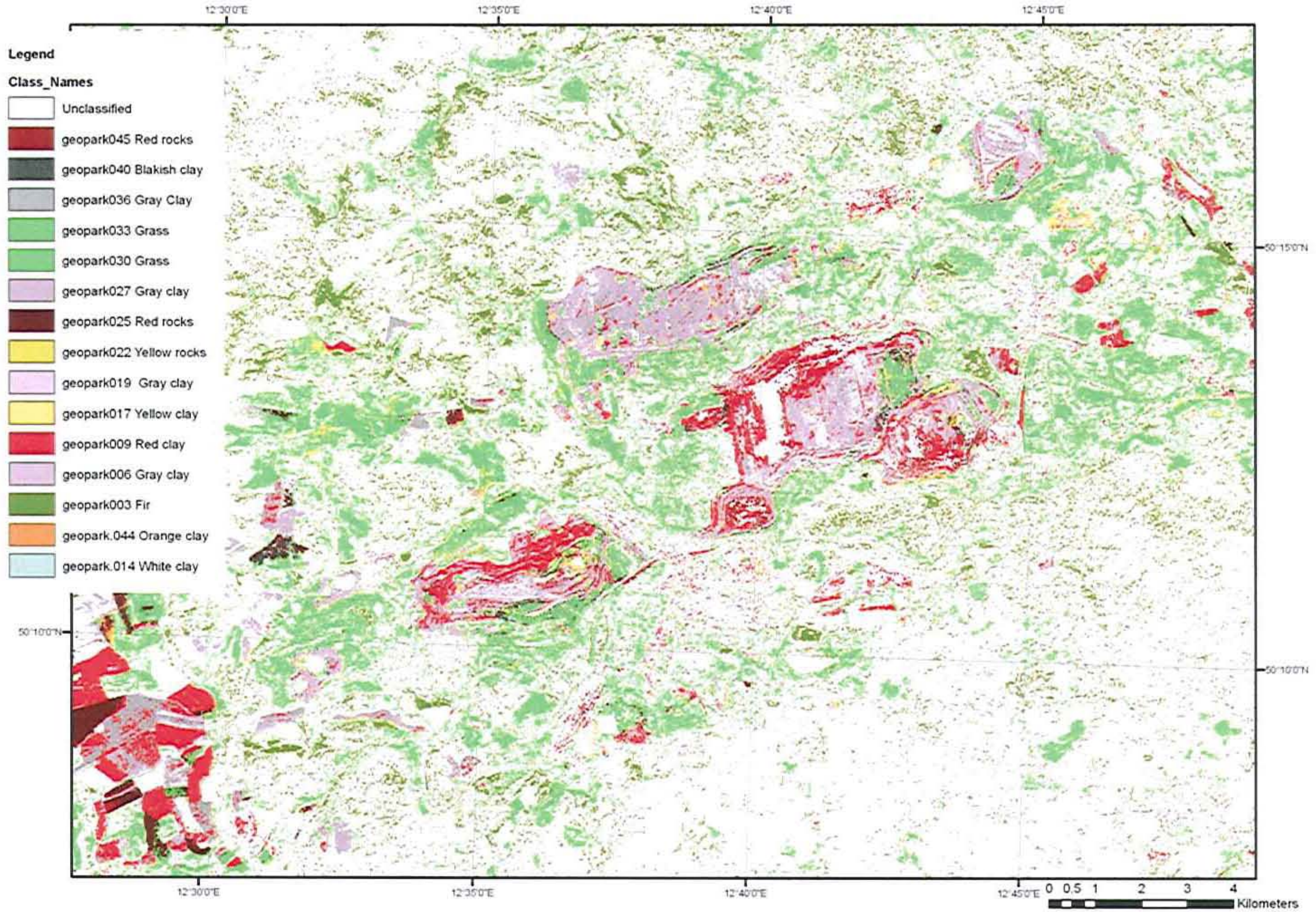
Appendix 6 : extension of mining works



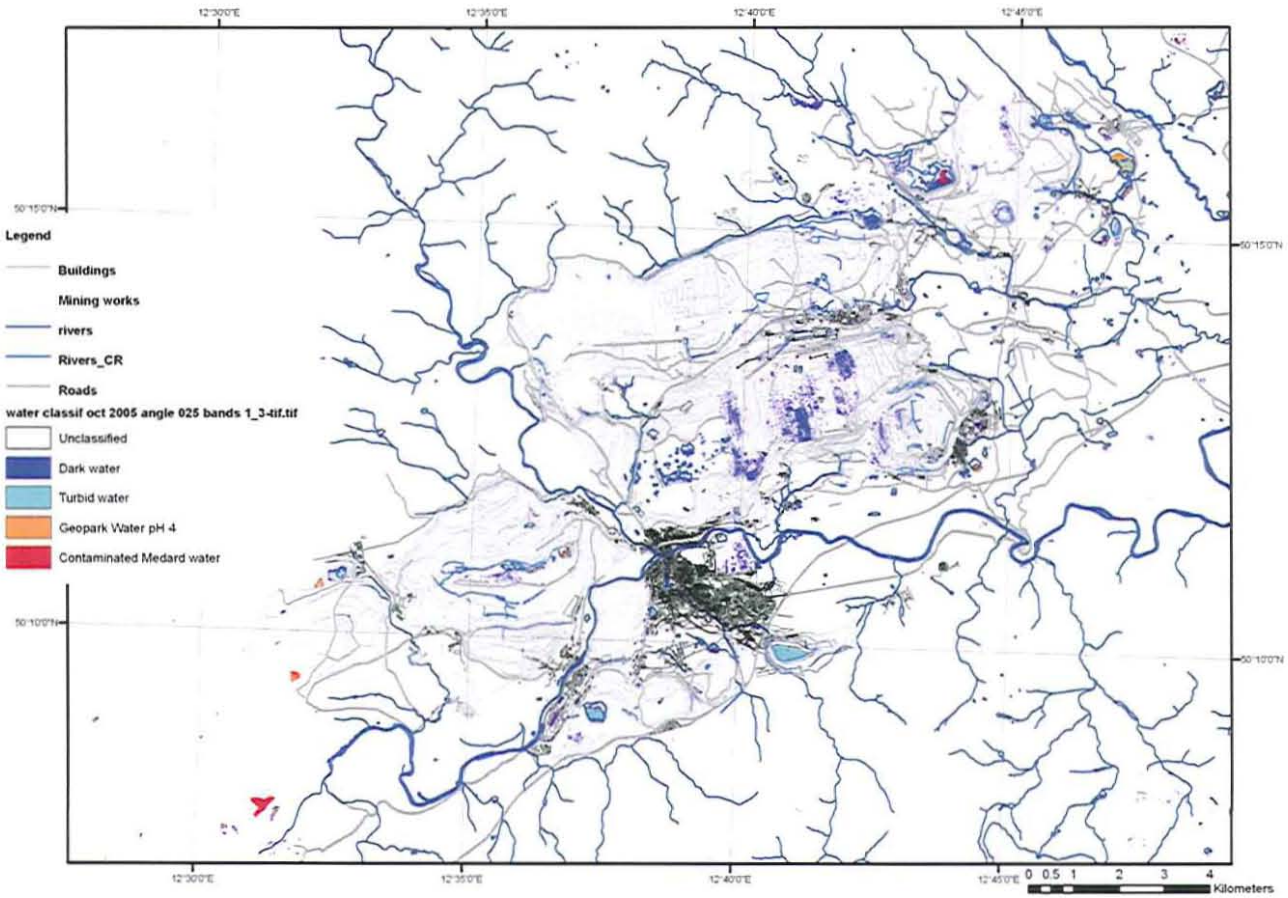
Appendix 7 : Aster Image October 2005



Appendix 8 : classification from Geopark field spectra



Appendix 9: classification of waters from selected image spectra



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