VOLCANOCLASTIC MINERALS OF SOME CZECHOSLOVAKIAN TONSTEINS AND THEIR ALTERATION

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ABSTRACT: In the Czechoslovak part of the Upper Silesian Coal Basin (Ostrava-Karvina Coal Basin), only part of the Upper Carboniferous (Namurian A, B, C and Westphalian A) is well developed, and tonsteins, which are clayey rocks or claystones, occur as thin, clayey interlayers in the coal seams. Two types of primary volcanic mineral assemblages were identified in four tonstein samples from different coal seams; the first type is characterized by the presence of biotite and sanidine, and the second by the presence of biotite, bytownite and Ca-amphibole. All tonsteins studied contained kaolinite minerals, volcanic quartz grains, crystals of zircon and apatite. Separated biotite flakes with an admixture of kaolinite layers were identified as 1M polytype. The flakes without kaolinite minerals were identified as epitactic overgrowth of 1M and complex polytypes, and twinned crystals of 2M₁ polytype. Kaolinitization of biotite flakes was observed in all tonstein samples studied. Kaolinite single layers (7 Å) as well as two-layer polytype of kaolinite minerals (14 Å) sandwiched between biotite layers (10 Å) were identified by HRTEM imaging.

Tonsteins are clayey rocks (claystones) occurring as thin interlayers in Carboniferous coal seams. They are of great lateral extent and tend to be uniform in both thickness and mineralogical composition. These properties distinguish tonsteins from other terrigenous rocks of Carboniferous strata and they are used, therefore, as excellent correlation aids for the identification of coal seams and detailed stratigraphic investigations.

Millot (1970), Williamson (1970), Price & Duff (1969), Dopita & Králík (1977), Bohor (1978), Spears & Kanaris-Sotiriou (1979), Ryer et al. (1980), Zhou et al. (1982) and Senkayi et al. (1984) concluded that tonsteins are formed in swamps as a product of in situ argillization of volcanic ash deposited in coal forming environments. Triplehorn & Bohor (1986) concluded that volcanic ash falling into a coal forming environment is likely to be preserved and may thus contribute to the mineral matter in coal. Such silicic (~70% SiO₂) volcanic ashes tend to be composed mostly of dust-sized particles of glass, with less than a few per cent of mineral grains such as quartz, feldspar, biotite, zircon and hornblende. After burial, the glass is altered into secondary clay minerals so that with increasing geological age the evidence of its volcanic origin becomes less and less obvious. Bohor (1985) concluded that the vitric components of rhyolitic volcanic ash alter to kaolinite when flushing is adequate to remove cations from the system, or to smectite when flushing is restricted. According to Bohor (1985), non-rhyolitic ashes generally alter to smectite rather than to kaolinite, sometimes even in coal-forming environments. The mineralogy of the final product is a function of composition and thickness of the starting material, geochemistry of the depositional environment, and ease of removal of cations from the...
system. Removal of cations is a very important factor for the formation of kaolinite minerals because it depends on the degree of leaching of silica and alkalies in the swamp environment.

In summary, tonsteins were formed in situ by disintegration of vitritic or crystalline tuffs. Apparently, the specific conditions of a coal forming environment determined the nature of the final products of disintegration of volcanic materials. The typical clay minerals of tonsteins are kaolinite minerals (particularly kaolinite) according to most papers published (e.g. Moore, 1964; Williamson, 1970; Loughnan, 1978).

The aim of this project was to analyse mineralogically the relicts of volcanoclastic materials in tonsteins and examine the alteration affecting biotite.

**MATERIALS AND METHODS**

**Samples**

Four samples of tonsteins from different coal seams of the Ostrava-Karviná Coal Basin were studied:

1. Seam no. 634, Suchá Member, Namurian C, Doubrava mine; finely crystalline tonstein (thickness 3 cm) from the upper part of the seam.
2. Seam no. 365, Jaklovec Member, Namurian A, Fucík 1 mine; the sample was taken from the centre of a layer of coarsely crystalline tonstein (thickness 20 cm) in the central section of the seam.
3. Seam no. 335, Jaklovec Member, Namurian A, Fucík 3 mine; a massive tonstein (thickness 10 cm) from the upper part of the seam.
4. Seam no. 252, Hrusov Member, Namurian A, Ostrava mine; coarsely crystalline tonstein (thickness 3 cm) from the bottom of the seam.

The stratigraphic positions of the coal seams 252, 335, 364 and 634 differ significantly, seam 252 being among the lowermost in the Carboniferous strata, and seams 335 and 365 intermediate. The vertical distance between seams 252 and 634 (one of the uppermost seams) is ~1600 m.

**Methods**

*X-ray diffraction (XRD).* Tonstein samples were ground to <5 μm and randomly-oriented mounts used for examination by X-ray powder diffraction. In order to obtain individual grains of volcanoclastic minerals (mica, feldspar, amphibole, zircon), the rock was disaggregated and the clay and coal matter were washed out. The grains were then hand-picked under a binocular microscope and investigated by single-crystal techniques.

*Optical analysis.* Standard optical techniques were used to identify minerals in thin sections, measure their particle size and determine the petrographic features of the tonsteins.

*High resolution transmission electron microscope (HRTEM) imaging.* Selected mineral particles were ground gently under acetone in an agate mortar. The flakes thus formed were allowed to settle from an acetone suspension on to carbon film coated copper grids. Flat lying flakes were used for the TEM investigation, whereas those standing vertical on the
Tonstein minerals

Carbon film were examined by lattice imaging. A JEOL-2000 FX electron microscope, equipped with a LAB6 filament, and a side-entry, double-tilt, high-resolution specimen stage, was used. This microscope operates at 200 kV and has a point-to-point resolution of 2.8 Å. The best lattice images were obtained from the lateral ends of upright flakes where the thickness was at a minimum.

Analytical electron microscopy. The same electron microscope, permanently equipped with a Si(Li) solid-state detector connected with a Tracor TN 524 data processing unit, was used to analyse the elemental content of grains. For microanalysis, flat-lying flakes nearly equal in thickness were preferred to the vertical flakes on which the HRTEM images were taken even though this procedure does not allow a direct one-to-one quantitative correspondence between HRTEM images and microcomposition, but yields only a qualitative composition. Microanalyses of biotite-kaolinite flakes were performed at 200 kV in the TEM mode, with an electron beam size of 500–600 Å and a current of 40 pA. Counting times ranged from 100–150 s. Raw X-ray spectra were processed with the Tracor’s SMTF program for semi-quantitative microanalysis of thin films, the emission peaks being corrected for background. The chemical analyses have an estimated accuracy of 3% relative to atomic percentages of the major elements analysed. The unit formula of biotite in the biotite-kaolinite intergrowths was calculated on the basis of 22 negative charges, assuming iron to be either all ferrous or all ferric. Microanalysis of amphiboles, feldspars and chlorites was performed using the LINK-system 860-2 and TESLA 200 electron microscope. Counting times ranged from 100–150 s and emission peaks were processed by ZAF4/FLS programs. The unit formulae of amphiboles were calculated on the basis of 23 negative charges.

RESULTS AND DISCUSSION

Mineralogy

The results obtained from XRD (powder and single-crystal), optical and microchemical analyses are summarized in Table 1. All samples of tonsteins contain abundant kaolinite minerals as shown by the powder patterns in Fig. 1. Kaolinite minerals were observed in various morphological forms, but tabular and vermicular aggregates are the most frequent. Powder XRD patterns, however, give information on an “average” kaolinite mineral. Thus it was not possible to decide whether individual morphological types of kaolinite minerals contain only kaolinite (possibly with different degrees of order) or also an admixture of another polytype (e.g. dickite). Unfortunately, even the single-crystal diffraction could not differentiate between polytypes, at least for the tabular crystals, because the 02l and 11l reflections were considerably smeared. If the powder profiles of 02,11 diffraction bands are interpreted assuming that the kaolinite mineral present is kaolinite, then it is a kaolinite with a medium to low degree of ordering in layer sequences (Hinckley index 0-9-0.5). To check for the possible presence of expandable clay minerals, tonstein samples were saturated with ethylene glycol but no smectite was detected. In addition to kaolinite minerals, the tonsteins contain mica, chlorite, quartz, feldspars, amphibole, zircon, apatite, and carbonates, the total content varying from ~5% (tonstein 252) to 10% (tonsteins 335 and 365).

Biotite was identified in all tonstein samples, phengite only in one (seam 634). Two different polytypes of phengite (2M1 and 3T) were determined by single-crystal diffraction
TABLE 1. Qualitative mineralogical analysis\(^1\) of tonsteins from selected coal seams of the Ostrava-Karvina Coal Basin.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Coal seam no.</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>634</td>
<td>365</td>
<td>335</td>
<td>252</td>
</tr>
<tr>
<td>Kaolin minerals(^2)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Biotite</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Phengite</td>
<td>*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chlorite</td>
<td>*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Quartz</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Sanidine</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Ca-amphibole</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Zircon</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Apatite</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Carbonates</td>
<td>-</td>
<td>*</td>
<td>*</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\) The presence of the minerals is marked by (*). XRD analysis (powder and/or single crystal), microchemical and optical analyses were used for identification.

\(^2\) Dominant minerals in all samples studied.

The chemical composition of the phengite is represented by its crystallochemical formula in Table 3.

Chlorite was observed as strongly deformed flakes in tonstein 634. Its mean chemical composition can be written as:

\[
(Mg_{4.66}Fe_{0.72}Al_{0.59}Ti_{0.02}Ca_{0.02})(Si_{3.15}Al_{0.85})O_{10}(OH)_8.
\]

The presence of a small amount of chlorite was also detected in tonstein 252 (powder XRD pattern, Fig. 1).

Quartz, apatite, and zircon were identified in all samples of tonsteins. Quartz grains exhibit a distinct angular, elongate morphology characteristic of volcanic quartz. Several rounded bipyramidal grains without prismatic faces (similar to those described by Zhou \textit{et al.}, 1982) were observed by scanning electron microscopy (SEM) and were interpreted as \(\beta\)-form quartz crystals.

Sanidine appears in tonsteins 634, 365 and 335 as shards of primary volcanic material, the amounts in 335 and 365 being quite large (Fig. 1). Some sanidine crystals or shards exhibit a relatively low degree of alteration to kaolinite minerals. The chemical composition of sanidine grains from all tonsteins is nearly constant (Fig. 2). The unit-cell parameters indicate a high degree of disorder in the \((Si,Al)\) distribution (Kroll \& Ribbe, 1987), which is characteristic of the sanidine structure.

Bytownite was identified only in tonstein 252. The range of composition of bytownites studied is portrayed in the \(Ab-Or-\)An triangular diagram in Fig. 2.

Individual amphibole crystals were separated from the tonstein of coal seam no. 252 and from XRD belong to the tremolite-actinolite series. Hawthorne’s (1981) diagram displays the results of microchemical analysis of these crystals (Fig. 3) whose composition spread widen and vary from tremolite to magnesio-hornblende due to different amounts of Si.

Traces of secondary carbonates belonging to the ankerite-dolomite series were identified in tonsteins 335 and 365.
FIG. 1. X-ray powder diffraction patterns of the tonstein samples from coal seam nos.: (a) 634, (b) 365, (c) 252; K = kaolinite minerals, C = chlorite, Q = quartz, B = biotite, S = sanidine. Spacings in Å.
TABLE 2. Mica polytypes identified by X-ray single-crystal diffraction of flakes from tonsteins of selected coal seams of the Ostrava-Karvina Coal Basin.

<table>
<thead>
<tr>
<th>Coal seam no.</th>
<th>Micas</th>
<th>Presence of kaolin minerals</th>
<th>Number of flakes analysed</th>
<th>Polytype</th>
</tr>
</thead>
<tbody>
<tr>
<td>634</td>
<td>Biotite</td>
<td>Yes</td>
<td>3</td>
<td>$1M$</td>
</tr>
<tr>
<td></td>
<td>Phengite</td>
<td>No</td>
<td>3</td>
<td>$2M_1$</td>
</tr>
<tr>
<td>365</td>
<td>Biotite</td>
<td>Yes</td>
<td>6</td>
<td>$1M$</td>
</tr>
<tr>
<td>335</td>
<td>Biotite</td>
<td>No</td>
<td>1</td>
<td>$2M_1/2M_1^*$</td>
</tr>
<tr>
<td>252</td>
<td>Biotite</td>
<td>No</td>
<td>2</td>
<td>$1M$</td>
</tr>
</tbody>
</table>

* Twinned $2M_1$ polytype.
** Epitactic overgrowths of $1M$ and complex polytypes.

TABLE 3. Crystallochemical formulae* of phengite and biotite domains in separated flakes from tonsteins of selected coal seams of the Ostrava-Karvina Coal Basin.

<table>
<thead>
<tr>
<th>Coal seam no.</th>
<th>Biotites</th>
<th>Phengite</th>
</tr>
</thead>
<tbody>
<tr>
<td>634</td>
<td>2.63</td>
<td>3.28</td>
</tr>
<tr>
<td>365</td>
<td>2.65</td>
<td>0.72</td>
</tr>
<tr>
<td>335</td>
<td>2.66</td>
<td>1.63</td>
</tr>
<tr>
<td>252</td>
<td>2.39</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**Tetrahedra**

- $Si^{4+}$: 2.63
- $Al^{3+}$: 1.37

**Octahedra**

- $Al^{3+}$: 0.34
- $Mg^{2+}$: 0.96
- $Fe^{2+}$: 1.37
- $Mn^{2+}$: 0.02
- $Ti^{4+}$: 0.19
- vacancy: 0.12

**Interlayer**

- $K^+$: 0.86
- $Na^+$: 0.05

<table>
<thead>
<tr>
<th>Coal seam no.</th>
<th>Biotites</th>
<th>Phengite</th>
</tr>
</thead>
<tbody>
<tr>
<td>634</td>
<td>0.87</td>
<td>0.81</td>
</tr>
<tr>
<td>365</td>
<td>0.00</td>
<td>0.07</td>
</tr>
<tr>
<td>335</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>252</td>
<td></td>
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</tr>
</tbody>
</table>

* All Fe was calculated as Fe$^{2+}$; F and Cl were not determined.

**Kaolinization of biotite**

Biotite is present in tonsteins as both undeformed and deformed flakes. Fifteen flakes were examined for polytypism by single-crystal techniques and only two flakes did not contain kaolinite minerals in X-ray detectable amounts. The remaining flakes contained various amounts of kaolinite minerals which could be identified from basal diffractions in Weissenberg photographs. A typical altered biotite flake is shown in Fig. 4. It appears that the biotite and kaolinite are oriented with their [001]$^*$ directions approximately parallel, but a random orientation of domains in the $ab$ plane is very likely. All biotite flakes with an
admixture of kaolinite minerals were identified as 1M polytype (Table 2), the remaining two flakes without kaolinite being epitactic overgrowths of 1M with complex polytypes and twinned crystals of 2M1, respectively. The polytypes were identified by a comparison of calculated and observed intensity distribution along the 02l diffraction rows (Weiss & Wiewióra, 1986).

The presence of kaolinite minerals in the biotite flakes studied was verified by microchemical analysis. From X-ray energy spectra, Si, Al, Fe, Mg, Mn, Ti and K were detected. Atom percentages of Si, Fe + Mg + Mn, and Ti were plotted as a function of %K, and are illustrated in Fig. 5 for “biotite” flakes separated from tonstein 365. The %K is a measure of the biotite content in each flake. The data for analytical points on various flakes populate an apparent “solid-solution” between kaolinite (left) and biotite (right). This “solid-solution” is in fact a mixture of kaolinite mineral(s) and biotite. Calculated data corresponding to the theoretical mixtures of kaolinite mineral Al2Si2O5(OH)4 and biotite (K0.9Na0.1)(Fe1.3Mg0.9Al0.5Ti0.2Si2.3)(Si2.7Al1.3)O10(OH,F)2 are represented by dotted lines in Fig. 5. The crystallochemical formula of biotite represents approximately the average composition of pure biotite domains from tonsteins 335 and 365.

Crystallochemical formulæ of biotite domains in individual flakes from the tonsteins studied are given in Table 3. The composition of domains from 335 and 365 is very similar, but somewhat different compositions were obtained for biotite domains from tonsteins 252 and 634. The interlayer deficient biotites (e.g. from tonsteins 252 and 634) raise the question about the possible domains of other unidentified minerals, such as smectite or vermiculite, but no such minerals were found by XRD when ethylene glycolation or heating tests were applied to purified biotite concentrates. It should be noted that the existence of interlayer deficient biotites has been described in the literature, e.g. the content of interlayer cations ranges from 0.65 to 0.85 (half-cell formulæ) in 46% of the 395 biotites listed in Ushakova's monograph (1971).
The replacement of biotite layers by kaolinite minerals is probably a result of leaching of alkalies (particularly K) and silica in the acid swamp environment. The kaolinization is accompanied by drastic structural and chemical changes so that the structure of biotite may be completely destroyed. In agreement with Ahn & Peacor (1987), we believe that kaolinization of biotite may involve the dissolution of biotite layers and a crystallization of kaolinite layers. From the constant composition of biotite in the biotite-kaolinite mineral assemblages, we infer that the dissolution of biotite was congruent, whatever the degree of kaolinization.

Using HRTEM imaging, kaolinization of biotite was studied on selected biotite flakes from tonsteins 335 and 365 in order to characterize directly the intergrowths of 7 Å and 10 Å layers. As an example, the euhedral morphology of one of the biotite flakes analysed can be seen in the SEM photo in Fig. 6a. The results of HRTEM imaging enabled us to draw the following conclusions: (1) The dissolution of biotite layers occurs inside the biotite crystals and is coupled with ingrowths of kaolinite layers. (2) In the domains of host crystals...
Fig. 4. X-ray Weissenberg photograph of the biotite flake separated from the tonstein of coal seam no. 634 containing kaolinite minerals (K). Zero level, axis of rotation [310], unfiltered Cu-Kα radiation.

Fig. 5. The relation between K (atomic %) and Si, Fe + Mg + Mn, Ti (atomic %) for a biotite flake separated from the tonstein of coal seam no. 365. Atomic percentages were determined by microchemical analysis at different points. Calculated data corresponding to theoretical mixtures of the “end-members” biotite and kaolinite minerals are shown by dotted lines.
Fig. 6. (a) Scanning electron micrograph of a biotite flake separated from the tonstein of coal seam no. 365 (scale bar = 0.1 mm). (b) 1D-HRTEM image of a section of the flake shown in (a) featuring biotite layers (M) and an interlayered single layer of kaolinite (K). (c) The interlayering of biotite (M) and kaolinite (K) layers with a predominance of kaolinite minerals over biotite. In the kaolinite domains where the specimen is thick (bottom left), a two-layer polytype (14 Å) is visible. The 001 diffraction rows (left) of the kaolinite minerals are superimposed on those of biotite. Indexing of kaolinite minerals diffraction spots is based on the two-layer polytype cell. (d) A schematic interpretation of the K–M and/or M–K contacts observed in (c) that includes lattice spacings intermediate (plus or minus increments ε and δ) between 7 and 10 Å.
where the intensity of alteration is relatively low (predominance of biotite over kaolinite minerals) the interlayering of biotite layers and single kaolinite layers (7 Å) can be observed (Fig. 6b). In those domains where the intensity of alteration is relatively high (predominance of kaolinite minerals) two-layer polytypes of kaolinite minerals (14 Å) were also found (Fig. 6c). (3) Along the kaolinite-biotite or biotite-kaolinite interfaces the interlayer spacings (along c*) are intermediate between 7 and 10 Å (Fig. 6c). Such variability of distances is inherent to the distribution of biotite sub-units (2:1 layer, interlayer), itself constrained by various topologies resulting from the necessary charge balance on a local scale (Fig. 6d).

A similar alteration mechanism has been described by Ahn & Peacor (1987), their interpretation being that a single biotite layer (10 Å) is replaced by two kaolinite layers (2 × 7 Å). However, our HRTEM observation of several biotite flakes shows that kaolinite single layers (7 Å) sandwiched between biotite layers are as frequent as two layers of kaolinite minerals (14 Å). Therefore, Ahn & Peacor’s mechanism may not be the only one possible.

Banfield & Eggleton (1988) showed two stages of weathering of igneous biotite from weathered granitoids: (1) Biotite transforms to vermiculite primarily by minor organization of the 2:1 layer involving replacement of K by hydrated interlayer cations. (2) Crystallization of kaolinite epitactically on to existing layers in connection with goethite which develops from a poorly crystalline iron oxyhydroxide. Even though this mechanism appears feasible, particularly under conditions open to the action of weathering agents, the presence of vermiculite in our samples could not be ascertained.

Domains of kaolinite minerals and biotite in vermicular aggregates characteristic of all tonsteins studied were also identified. The aggregates exhibit a typical columnar habit, with striated faces. Their colour is yellow to brown owing to the presence of fine coal matter. The “macro-domains” of biotite and kaolinite minerals in vermicular aggregates were identified by microprobe analyses. As in Fig. 5, percentages of Fe + Mg + Mn were plotted against %K. The plot in Fig. 7 is for aggregates separated from tonsteins 335, 365 and 634. In addition, variations in K, Fe, Al and Mg contents were monitored along lines parallel to the elongation of the aggregate. An SEM photograph showing a vermicular aggregate from tonstein 335 (Fig. 8a) features such a scanning line marked in white. The energy-dispersive X-ray spectrum from a biotite domain in the aggregate is presented in Fig. 8b. As can be seen in Fig. 8c, a significant decrease in Mg content, and an increase in Al (compared to the biotite domain at the starting point of the line scan) indicate the location of kaolinite domains. The domains are approximately 5 μm across; the sizes of kaolinite domains in aggregates from tonstein 335 generally exceed those from tonsteins 365 and 634.

CONCLUSIONS

(1) The study of four tonstein samples originating from different coal seams of the Ostrava-Karviná Coal Basin revealed the presence of two types of primary volcanic mineral assemblages. The first type (tonsteins from coal seam nos. 335, 365 and 634) is characterized by the presence of biotite and sanidine, the second (tonstein from coal seam no. 252), by the presence of biotite, bytownite and Ca-amphibole (tremolite to magnesio-hornblende). All tonsteins studied contain crystals of zircon, volcanic quartz grains, and apatite.
(2) The main components of all tonstein samples studied are kaolinite minerals. No other type of clay mineral was found. The content of non-clay minerals varies from ~5% (tonstein 252) to 10% (tonsteins 335 and 365).

(3) All biotite flakes (separated from individual tonsteins) containing an admixture of a kaolinite mineral were identified as 1M polytype. The flakes without a kaolinite mineral were identified as epitactic overgrowths of 1M and complex polytypes, or as twinned crystals of 2M₁ polytype.

(4) Kaolinization of biotite flakes was observed in all tonstein samples studied. Kaolinite single layers (7 Å) sandwiched between biotite layers (10 Å) are as frequent as layers of two-layer (14 Å) polytype of kaolinite minerals. Along the kaolinite-biotite or biotite-kaolinite interfaces, the interlayer spacings (along c*) are intermediate between 7 and 10 Å).

ACKNOWLEDGMENTS

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Fig. 8. (a) Scanning electron micrograph of a kaolinite-biotite vermicular aggregate from the tonstein of coal seam no. 335. Contents of Mg and Al were recorded along the line scan (white line). (b) Energy-dispersive X-ray spectrum from a biotite-rich domain in the aggregate shown in (a). (c) Line-scan representation showing the changes in Mg and Al content. The increasing Al and decreasing Mg contents (relative to the biotite domain at the starting point of the line-scan) indicate kaolinitic domains. The magnitude of the Al content was scaled to 1/2.

REFERENCES


