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# Compaction of lignite: a review of methods and results

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ABSTRACT:

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The published peat:coal compaction ratios range from 1.1:1 to 60:1 and from 1.1:1 to 11:1 for lignites. These probably represent realistic end-member values for the degree of compaction during the transformation of peat into lignite and then to coal. Hence, in many cases, the obtained values of the compaction ratio are under- or overestimated with reference to the entire coal seam.

This study focuses on the changes of thickness between a peat bed and the resulting lignite seam. The fundamental question is how many times the thickness of the peat bed, prior to covering the mire by the overburden, was greater than the present-day thickness of the lignite seam.

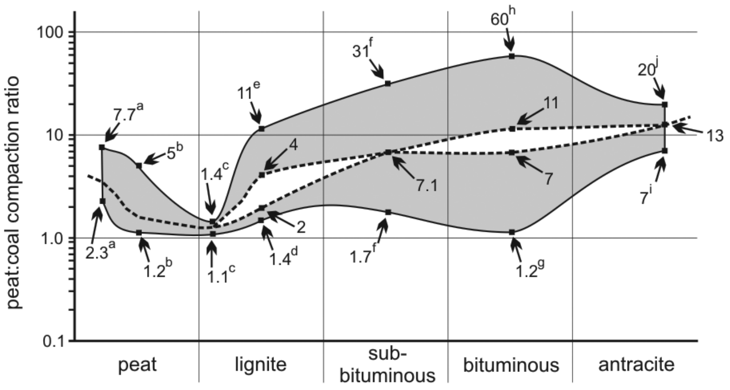
The majority of methods reported in this paper cannot be used directly to quantify the amount of compaction of the lignite seam. In this context, the only category of methods which allow a direct estimation of the peat:lignite compaction ratio are the so-called stratigraphic methods. Therefore, based on comparison of the initial peat bed thickness with lignite seam thickness, the most accurate peat:lignite compaction ratio ranges from 2:1 to 4:1.

**Keywords:** Peat; Lignite; Coal; Compaction process; Compaction ratio; Peat:lignite compaction ratio.

## INTRODUCTION

The process of compaction plays a significant role in sedimentological, stratigraphic, and palaeotectonic analyses (e.g. Van Hinte 1978; Miall 1981; Doglioni and Goldhammer 1988; Allen and Allen 1990; Ten Veen and Kleinspehn 2000; Michon *et al.* 2003; Volkov 2003; Rajchl and Uličný 2005; Widera *et al.* 2008; Rajchl *et al.* 2009; Widera and Hałuszczak 2011). Such processes are relatively well-known and accepted in the case of mineral deposits (Baldwin and Butler 1985; Sheldon and Retallack 2001). However, the effects of compaction on organic-rich rocks such as peat, lignite and coal are still controversial. This is best seen in the variety of published research results (Text-fig. 1). Thus, a better understanding of the compaction process appears to be one of the most important challenges for researchers dealing with the geology of coal-bearing deposits.

The relationship between the original thickness of the peat and the thickness of the resulting coal is termed in different ways. The following factors of compaction are most often used in the literature: 'compaction coefficient' (e.g. Hurník 1972, 1990; Widera 2013a, 2013b), 'shrinkage coefficient' (Zaritsky 1975), 'compression ratio' (e.g. Collinson and Scott 1987; Kojima *et al.* 1998), 'consolidation coefficient' (Widera 2002; Widera *et al.* 2007), or 'compaction ratio' (e.g. Ting 1977; Ryer and Langer 1980; DeMaris *et al.* 1983; Law *et al.* 1983; McCabe 1984, 1987; Elliot 1985; White 1986; Winston 1986; Courel 1987; Salinas *et al.* 1990; Gayer and Pešek 1992; Nadon, 1998; Greb *et al.* 2003; Petersen *et al.* 2003; Rajchl and Uličný 2005; Rajchl *et al.* 2009; Jerrett *et al.* 2011; Flores 2013). As the most common, the term 'compaction ratio' will therefore be employed throughout this paper, particularly in the final sections.



Text-fig. 1. Graphic summary of minimum and maximum variations of the peat:coal compaction ratio given in the literature. The dotted line corresponds to the average values of the compaction ratio. Compiled from: [a] – Bloom (1964), [b] – Bird *et al.* (2004), [c] – Widera (2013a) [d] – Hurník (1990), [e] – Smith and Clymo (1984), [f] – White (1986), [g] – Nadon (1998), [h] – Winston (1986), [i] – cited by Ryer and Langer (1980), [j] – Elliot (1985)

The compaction of sedimentary rocks can be generally defined as a process leading to a reduction in sediment volume and an increase in sediment density (e.g. Baldwin and Butler 1985; Sheldon and Retallack 2001). Compaction plays an important role in all geological processes and is considered as diagenesis, or as a process that also modifies organic-rich sediments after their deposition (Ting 1977; Stach *et al.* 1975, 1982; Taylor *et al.* 1998). In this paper, compaction refers strictly to those physical, biological, and geochemical processes that affect the peat bed after burial (e.g. Hurník 1972, 1990; Hager *et al.* 1981; Hager 1993; Widera 2002, 2013a, 2013b; Widera *et al.* 2007). Compaction in this sense must be contrasted with the autocompaction process, which changes the properties of the peat during deposition prior to the burial of the mire (e.g. Gayer and Pešek 1992; Allen 2000; Bird *et al.* 2004; Long *at al.* 2006). However, it must be emphasised that the basal peat beds in a mire are partially (auto)compacted with reference to the near-surface peat layers (Falini 1965; McCabe 1984; Volkov 2003).

This paper aims: 1) to review all major methods of determining peat:coal compaction ratios and to provide conceptual frameworks for these methods; 2) to discuss compaction ratios obtained directly and indirectly by different methods; and 3) to identify and explain the paradox in the transition from peat to lignite.

| Group of methods | Category of methods | Coal rank | Source |
|---|---|---|---|
| indirect | density | peat | Bird et al., 2004; Van Asselen et al., 2009; Van Asselen, 2011 |
| | | lignite | Falini, 1965; Volkov, 1965 |
| | inclusions | lignite | Glockner, 1912; Ting, 1977 |
| | | bituminous | Teichmüller, 1955; Stach et al., 1975; Zaritsky, 1997; DeMaris et al., 1983; Gayer and Pešek, 1992 |
| | petrographic | lignite | Piwocki, 1975; Stout and Spackman, 1989; Hurník, 1990; Kojima et al., 1998; Widera, 2013a |
| | | subbituminous | White, 1986 |
| | | bituminous | Courel, 1978; Winston, 1986 |
| direct | stratigraphic | peat | Bloom, 1964; Haslett et al., 1998 |
| | | lignite | Hurník, 1972; Hager et al., 1981; Hager, 1993; Kasiński, 1984, 1985; Widera, 2002; Widera et al., 2007 |
| | | bituminous | this paper |

Table 1. Compilation of basic methods used to estimate the compaction ratio for coals of different rank

## METHODS OF ESTIMATING THE COMPACTION RATIO

There are many methods for calculating the amount of compaction, which is expressed as the compaction ratio. They can be grouped into different categories based on various criteria. In this paper, the classification proposed by Ryer and Langer (1980) is followed. These researchers subdivided the various methods used to quantify the peat:coal compaction ratio into four categories: 1) density; 2) inclusions; 3) petrographic; and 4) stratigraphic. Additionally, to achieve the stated objectives, these categories are grouped into indirect and direct methods (Table 1). The first group determines compaction of the mire constituents and/or coal seam; it means that the compaction of the whole seam can be estimated only indirectly. In contrast, the second group of methods allows direct quantification of the compaction ratio for the entire coal seam.

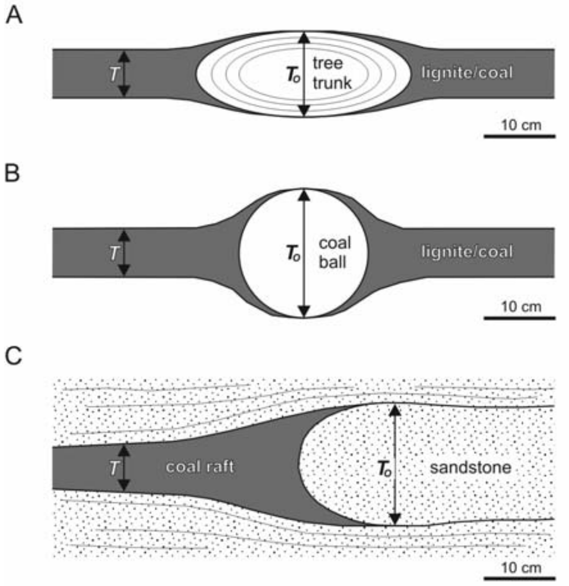
### Conceptual framework of indirect methods

#### *Density methods*

In general, this method is based on comparison of the density of uncompacted peat with that of compacted peat, lignite, or coal (Ryer and Langer 1980; Table 1). Using this approach, the difference between the dry bulk densities is usually determined for both measured (compacted) and initial (uncompacted) samples. It is calculated as the mass of an oven-dried sample divided by its total volume. The density method has been used successfully in the estimation of the amount of compaction of modern mires (e.g. Bird *et al.* 2004; Van Asselen *et al.* 2009; Van Asselen 2011). These studies reviewed the above-described method in detail; for more information the reader is directed to the papers cited.

#### *Inclusions methods*

In this case, compaction of originally flat-lying peat layers is compared to that of included incompressible or less compressible objects (Ryer and Langer 1980; Table 1). Due to the differential compaction of these objects and the surrounding lignite/coal, so-called ‘fish-tail’ forms are created (Gayer and Pešek 1992). These are expressed by the thickening of the more compressible lignite/coal towards less compressible objects such as tree trunks, coal balls or sandstones (Text-fig. 2).



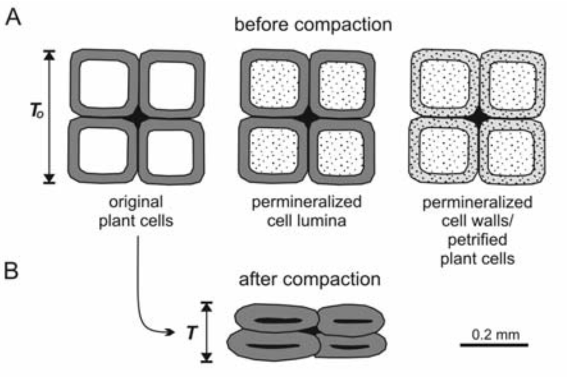
Text-fig. 2. The use of ‘fish-tail’ forms to calculate the compaction ratio. Visualization based on the concepts of various authors

This method enables calculation of the relative compaction ratio. Here, the original thickness of uncompacted objects, measured along the ‘fish-tail’ ends – $\boldsymbol{T_o}$, is divided by the thickness of the compacted and flat-lying lignite/coal bed – $\boldsymbol{T}$ (Text-fig. 2). Additionally, it is possible to estimate the extent of both autocompaction/self-compaction and compaction (Gayer and Pešek 1992). However, the most common method is the determination of the compaction ratio through the use of coal balls (Text-fig. 2B; Teichmüller 1955; Stach *et al.* 1975; Zaritsky 1975; DeMaris *et al.* 1983).

#### *Petrographic methods*

The petrographic methods rely on the measurement of the deformation of objects contained in the lignite/coal seam, where the original and undeformed shapes are known (Ryer and Langer 1980; Table 1). Calculating the amount of compaction at the micro-scale requires investigation of plant cells (Text-fig. 3); however, at the macro-scale, the most commonly employed included objects are xylites (Text-fig. 4) and clastic dykes (Text-fig. 5). In the case of xylites, the fossilized remains of trees such as roots, trunks, stems, branches, twigs and cones may be measured in the field.

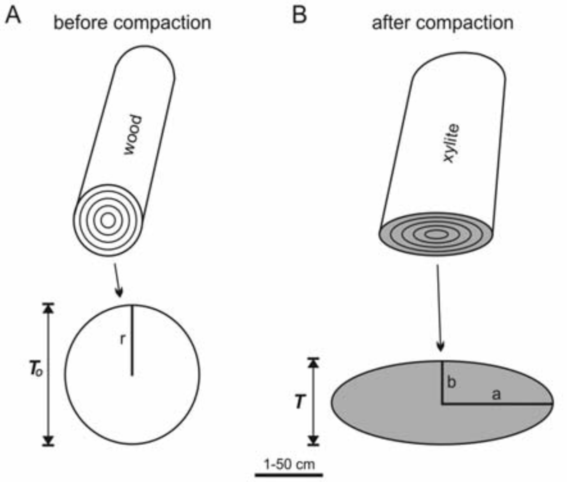
Compaction can be determined microscopically if undeformed and deformed cells or plant tissues are present in the seam under study. Such a case occurs when some parts of the seam are petrified, for example, in the form of coal balls. The uncompacted peat, therefore, may be preserved in the coal balls (Buurman 1972; Scott and Collinson 1983; Collinson and Scott 1987). The compaction ratio can then be derived by comparing



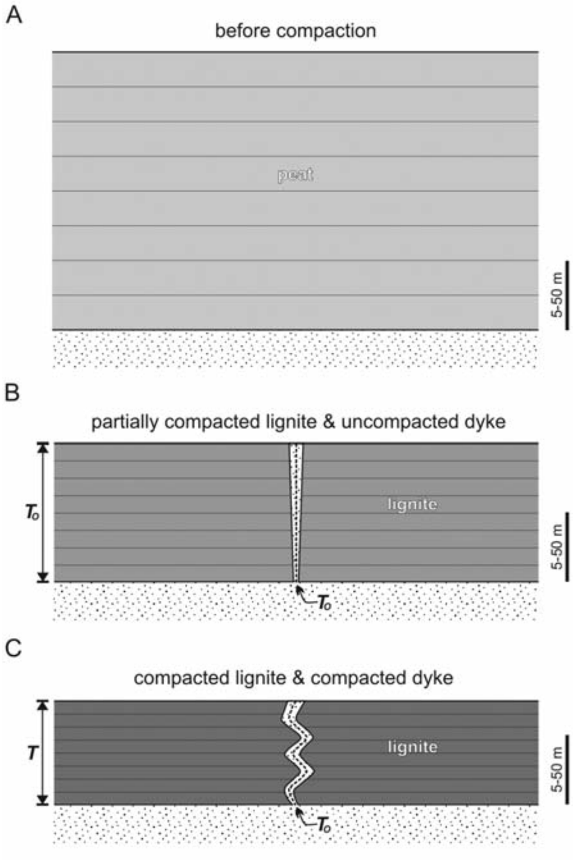
Text-fig. 3. The use of plant cells to calculate the compaction ratio. Redrawn with modification from Scott and Collinson (1983)

the thickness of the uncompacted plant cells – $\boldsymbol{T_o}$ (Text-fig. 3A) with that of the compacted ones – $\boldsymbol{T}$ (Text-fig. 3B; Ting 1977).

In the case of fossil wood, or xylite, compaction manifests in a flattening of the cross-section. The initial cross-section of wood (trunks, branches, roots, etc.) was round or very close to circular (Text-fig. 4A). In contrast, because of compaction, the circular cross-section of the wood is transformed into an elliptical one (Text-fig. 4B). No account is taken of the compressibility of the wood cells or of changes in length of the xylites because these have a negligible impact on the results (Piwocki 1975; Stout and Spackman 1989; Kojima *et al.* 1998; Widera 2013a). Although the radius of the tree (r) before compaction is not known, the compaction ratio ($\boldsymbol{Cr}$) can be readily determined by comparing the area of the circle with that of the ellipse. The semi-major (a) and semi-minor (b) axes of the ellipse can be easily measured in the field. Because $\boldsymbol{T_o}/\boldsymbol{T}$ is equal to r/b (Text-fig. 4), the final equation for the calculation of the compaction ratio for xylites contained in the lignite/coal seam is as follows: $\boldsymbol{Cr} = (a/b)^{0.5}$ (Widera 2013a).



Text-fig. 4. The use of xylites (fossil woods) to calculate the compaction ratio. Redrawn with modification from Widera (2013a)



Text-fig. 5. The use of clastic dykes to calculate the compaction ratio. Visualization based on the concepts of various authors

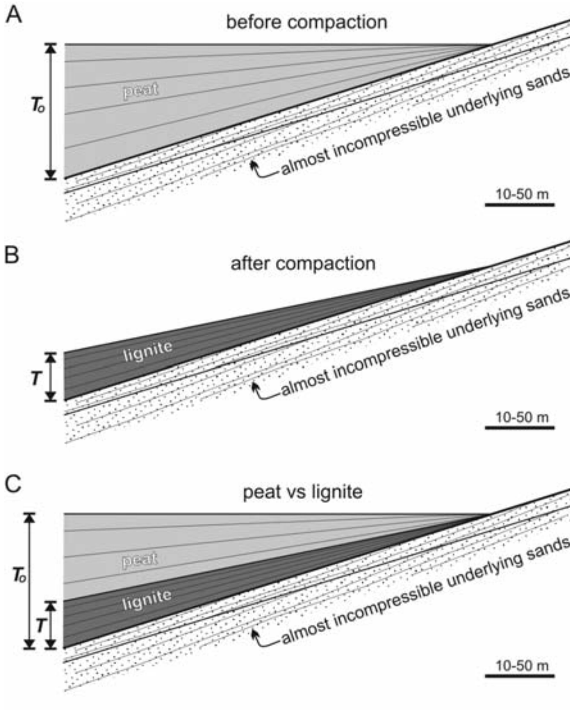
The compaction ratio is sometimes estimated using deformations of clastic dykes piercing the lignite/coal seam (Text-fig. 5). This method is based on the vertical shortening of the length of the dyke during compaction (e.g. Courel 1987; Hurník 1990). First, the true length of the dyke is measured – $\boldsymbol{T_o}$, which refers to the seam thickness when the dyke intruded into it – $\boldsymbol{T_o}$ (Text-figs 5B, 5C). Then, the compaction ratio ($\boldsymbol{Cr} = \boldsymbol{T_o}/\boldsymbol{T}$) between the above-mentioned $\boldsymbol{T_o}$ and $\boldsymbol{T}$ corresponding to the present-day thickness of the lignite/coal seam may be calculated.

## Conceptual framework of direct methods

### *Stratigraphic methods*

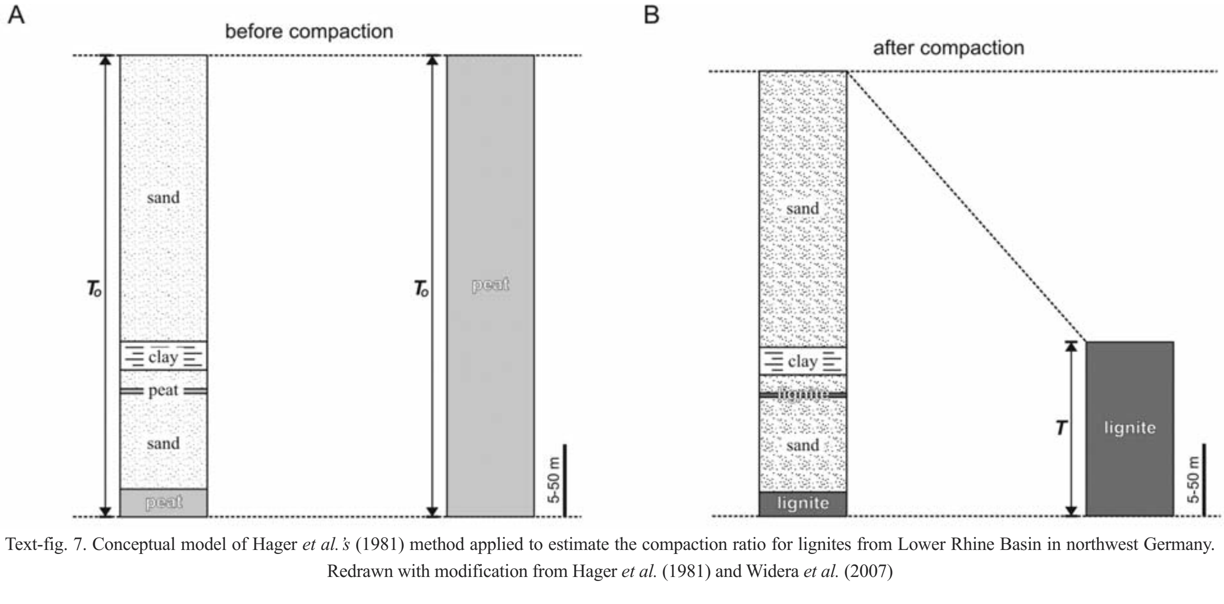
There are at least three different approaches to directly estimate the compaction ratio of organic-rich sediments. They belong to the category of stratigraphic methods as distinguished by Ryer and Langer (1980; Table 1). Conceptually, all of them rely on a comparison of the thickness of the original peat bed with the thickness of the resulting lignite/coal seam. To estimate the peat:lignite/coal compaction ratio, the initial thickness of peat is reconstructed using various stratigraphic methods that are characterized below (Hurník 1972; Hager *et al.* 1981; Hager 1993; Widera 2002; Widera *et al.* 2007).

The first of these methods was established by Hurník (1972) for the investigation of the lignites from the North Bohemian Basin in the northwest Czech Republic. This method relies on identifying in detail the clastic sediments that underlie the lignite seam (Text-fig. 6). It takes into consideration the origin and slope of the pre-depositional surface; that is, the inclination of the top surface of the clastic sediments. Here, it is assumed that the above-mentioned palaeosurface is characterized by the same angle of dip, both now (Text-fig. 6A) and during the development of the mire (Text-fig. 6B). Such a situation has been observed in some parts of the North Bohemian Basin (e.g. Hurník 1972; Rajchl and Uličný 2005; Rajchl *et al.* 2009). The mire surface prior to burial was almost horizontal, in contrast to the tilted top of the present-day lignite seam. However, knowing the initial peat thickness – $T_o$, and the lignite seam thickness – $T$, they may be readily compared. In this case, the peat:lignite compaction ratio ($Cr = T_o/T$) is or should be approximately the same along the entire line of the cross-section (Text-fig. 6C).

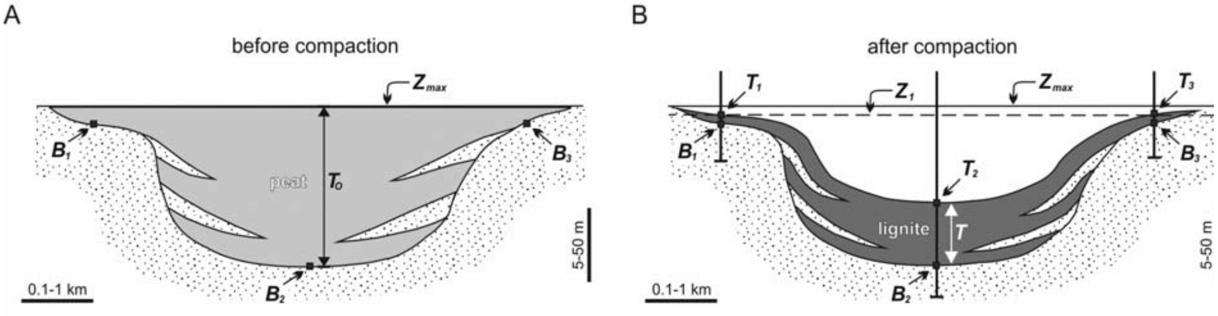


Text-fig. 6. Conceptual model of Hurník's (1972) method applied to estimate the compaction ratio for lignites from the North Bohemian Basin in the north west Czech Republic. Graphic interpretation by the author of this paper

Hager *et al.* (1981) created the second method of this category for lignites from the Lower Rhine Basin in northwest Germany. These researchers compared two borehole profiles: one with mainly lignite and a second one with mainly clastic sediments. Conceptually, the method is based on the fact that the investigated lignite seam is laterally accompanied by isochronous clastic deposits (Text-fig. 7). Such a correlation of lignites and clastics is possible because the Lower Rhine Basin is an area where clearly distinguishable marine deposits pass laterally into terrestrial ones containing lignites (e.g. Hager *et al.* 1981; Hager 1993;



Text-fig. 7. Conceptual model of Hager *et al.'s* (1981) method applied to estimate the compaction ratio for lignites from Lower Rhine Basin in northwest Germany. Redrawn with modification from Hager *et al.* (1981) and Widera *et al.* (2007)



Text-fig. 8. Conceptual model of Widera's (2002) and Widera *et al.*'s (2007) method applied to estimate the compaction ratio for lignites from sedimentary basins in central Poland. Redrawn with modification from Widera (2002) and Widera *et al.* (2007)

Schäfer *et al.* 1995, 2004, 2005; Michon *et al.* 2003; Schäfer and Utescher 2014). Taking into account changes in porosity of clastics with thin lignite intercalations in one of the two borehole successions, the original peat thickness was determined. It was then assumed that the initial thickness of the peat in the second borehole must have been the same as that of the sediments in the first borehole (Text-fig. 7A). Finally, the peat:lignite compaction ratio could be derived by comparing the initial thickness of the almost incompressible clastics, which is equal to the thickness of the peat before compaction – $T_o$, and the present-day compacted lignite seam thickness – $T$ (Text-fig. 7; Hager *et al.* 1981).

The last of the stratigraphic methods was proposed by Widera (2002) and Widera *et al.* (2007) and is conceptually close to the above-described methods proposed by Hurník (1972) and Hager *et al.* (1981). Unfortunately, the latter two methods cannot be applied in their original form in the case of the lignite seams in central Poland. Firstly, the deposits underlying the lignites are not well exposed and it is therefore impossible to identify clearly their origin and the slope of the predepositional surface (Hurník 1972). Secondly, there are no marine horizons available for the proper correlation of the mineral (non-marine) deposits and the lignites in the case of most of the Polish lignite deposits (Hager *et al.* 1981). The method presented here combines field observation of the lignite seam and the borehole data with the results obtained from studies of modern peat-forming environments. Conceptually, this method relies on reconstructing the maximum height ($Z_{max}$) of the mire surface before compaction; that is, prior to burial (Text-fig. 8A). The present-day architecture of the lignite-seam is well known from boreholes (Text-fig. 8B). In this method, the peat:lignite compaction ratio is, of course, expressed as $Cr = T_o/T$. However, the maximum height of the mire surface ($Z_{max}$) is estimated using the borehole data with thin lignite layers located in the marginal parts of the lignite seam (Text-fig. 8). For more information, including the basic equations, the interested reader is referred to papers by Widera (2002) and Widera *et al.* (2007).

## VARIATIONS OF THE COMPACTION RATIO WITH DISCUSSION

### Density methods

Measurements based on sediment dry bulk density are most often used to quantify the amount of subsidence due to compaction of Holocene peat. The recalculated compaction ratio for organic-rich deposits in the Rhine-Meuse delta is up to 1.7:1; however, its average value is ~1.4:1 (Van Asselen *et al.* 2009; Van Asselen 2011). In the case of the mangrove peats in Singapore, the average compaction ratio ranges between 1.2:1 and 2.2:1 (Text-fig. 1), with a maximum value of up to 5.0:1 (Bird *et al.* 2004). The advantage of this method, supported by $^{14}$C dating, is that it is possible to determine quite precisely not only the age of the peat but also the accumulation and compaction rates. However, this approach is limited to relatively young organic-rich sediments; that is, the late Pleistocene and Holocene peats.

There are only two examples in the literature where the peat to lignite compaction ratios have been estimated using the density measurements (Falini 1965; Volkov 1965). The average values of the peat:lignite compaction ratio obtained by Falini (1965) and Volkov (1965) were 10:1 and 2.5:1 respectively. It seems that the latter value of 2.5:1 is more realistic in the context of results discussed in this present contribution (Table 2).

| Peat:lignite thickness ratio | | Age | Lithostatigraphy and location | Method | Material | Source |
|---|---|---|---|---|---|---|
| average | range | | | | | |
| 10:1 | - | - | - | density | ash and water content | Falini, 1965 |
| 2.5:1 | - | - | - | density | ash and water content | Volkov, 1965 |
| 4:1 | - | Paleocene | Fort Union Group, North Dakota, USA | inclusions | plant tissues | Ting, 1977 |
| 4:1 | 2:1–7:1 | Eocene | Buchanan Lake Formation, Canadian Arctic | petrographic | trunks, branches (xylites) | Kojima et al., 1998 |
| 4:1 | 3:1–5:1 | Miocene | Ścinawa Formation, Poland | petrographic | trunks, branches, twigs, etc. (xylites) | Piwocki, 1975 |
| 3:1 | - | Miocene | Brandon Lignite, Vermont, USA | petrographic | compressed woods (xylites) | Stout and Spackman, 1989 |
| 1.2:1 | 1.1:1–1.4:1 | Miocene | Poznań Formation, Poland | petrographic | trunks, branches, twigs, etc. (xylites) | Widera, 2013a |
| 4:1 | 3:1–6:1 | Miocene | Most Formation, Czech Republic | stratigraphic | reconstructed original peat thickness | Hurník, 1972 |
| 3:1 | 2.7:1–3.5:1 | Miocene | Ville Formation, Germany | stratigraphic | reconstructed original peat thickness | Hager et al., 1981; Hager, 1993 |
| 2.5:1 | 2.3:1–2.6:1 | Miocene | Ścinawa Formation, Poland | stratigraphic | reconstructed original peat thickness | Widera, 2002; Widera et al., 2007 |
| 2.2:1 | 1.7:1–2.9:1 | Miocene | Ścinawa Formation, Poland | stratigraphic | reconstructed original peat thickness | Kasiński, 1984, 1985 |
| 2:1 | 1.8:1–3.5:1 | Miocene | Poznań Formation, Poland | stratigraphic | reconstructed original peat thickness | Widera, 2002; Widera et al., 2007 |

Table 2. Some examples of the peat to lignite compaction ratio obtained using various methods

## Inclusions methods

The vast majority of results based on investigations of inclusions such as tree trunks, coal balls and sandstones (Text-fig. 2) have been obtained for high-rank coals. Thus, the compaction ratios calculated for bituminous coals of Pennsylvanian age range from 3:1 to 20:1 (Teichmüller 1955; Stach *et al.* 1975; DeMaris *et al.* 1983). The average value, for example, for coal balls from the Illinois Basin (USA) and the Donets Basin (Ukraine) is 5:1 (Zaritsky 1975; DeMaris *et al.* 1983). On the other hand, analysis of the coal rafts in the Westphalian deposits of south Wales has yielded peat:coal compaction ratios ranging from 3:1 to 7.5:1, with an average value of 5:1 (Gayer and Pešek 1992). This research showed that these coals had undergone partial compaction – that is, autocompaction/self-compaction – prior to their burial. This peat:coal autocompaction ratio ranges between 1.3:1 and 5.7:1 (Gayer and Pešek 1992).

In the case of lignites, only one paper has described the method which has been employed. Taking into account the ‘draping of coal over a tree stump at the base of a seam’ the calculated peat:lignite ratio is 2.5:1 (Glockner 1912). It must be clearly stated that this result is slightly lower than the range of compaction ratio values obtained for the Miocene lignites in northwest Germany using the stratigraphic method by Hager *et al.* (1981) and Hager (1993).

## Petrographic methods

Pennsylvanian coals from the Illinois Basin (USA) are characterized by peat:coal compaction ratios ranging from 3:1 to 60:1, based on deformations of plant tissues compared with those preserved in coal balls (Text-figs 1, 3; Winston 1986). Using the same method, Ting (1977) estimated the compaction ratio for the Paleocene lignites from North Dakota (USA), obtaining an average value of 4:1 for the peat to lignite transformation (Table 2; Ting 1977).

In contrast to the above-described results, based on measurements of compacted cross-sections of fossil wood, most of the results presented here are just obtained for lignites (Text-fig. 4). An exception is the subbituminous Wyodak coal seam in the Powder River Basin, Wyoming (USA). The peat:coal compaction ratios calculated for these coals range from 1.7:1 to 31:1, averaging 7.1:1 (Text-fig. 1; White 1986). The reason for this is that xylites (fossil woods) in lignites are more widely distributed than in higher-rank coals. Here, at least four examples of the compaction ratio calculations for lignites can be given (Table 2). First, using this method Piwocki (1975) quantitatively estimated the compaction process for the Miocene lignites of the Ścinawa Formation from western Poland where the average peat:lignite compaction ratio is 4:1, ranging from 3:1 for detritic lignite to 5:1 for xylitic lignite (Piwocki 1975). The second example comes from the Eocene lignites of the Upper Coal Member of the Buchanan Lake Formation in a Canadian Arctic archipelago. In this case, horizontal trunks and branches were measured; hence, the peat:lignite compaction ratios range from 2:1 to 7:1, averaging 4:1 (Kojima *et al.* 1998). Another example includes measurements of xylites found in the early Miocene Brandon lignite (Vermont, USA). The average compaction ratio for the above-mentioned lignites is 3:1 (Stout and Spackman 1989). The last example comes from the middle Miocene lignites of the Mid-Polish Member (Poznań Formation) in central Poland. On the basis of measurements of xylites (trunks, branches, twigs, etc.), the calculated peat:lignite compaction ratios ranged from 1.1:1 to 1.4:1, averaging 1.2:1 (Table 2; Widera 2013a).

The results given above and compiled in Table 2 require a brief commentary. As described, Stout and Spackman (1989) suggest that results should be treated as an absolute minimum value of compaction. On the other hand, the author of the present contribution specified that the magnitude of xylite compaction (***Cr*** = 1.2) is approximately 60% in relation to the compaction of the entire lignite seam (Widera 2013a). The value 60% has been previously estimated using the stratigraphic method (***Cr*** = 2.0; Widera 2002; Widera *et al.* 2007). Such a comparison of the compaction effects was only possible in the case of the above-mentioned Miocene lignite seam, representing the Poznań Formation in central Poland. This is probably the only seam for which the peat:lignite compaction ratios were determined by two methods and then compared with each other (Table 2).

The measurements of clastic dykes contained in the coal seam (Text-fig. 5) also belong to this category of methods. On the basis of the vertical shortening of sandstone dykes cutting Carboniferous and Permian coal seams in the Massif Central (France), Courel (1978) estimated a peat:coal compaction ratio of 3.5:1. As this researcher stated, the obtained ratio refers to the late stage of the compaction process (Courel 1987).

Hurník (1990) determined peat:lignite compaction ratios between 1.4:1 and 1.7:1 for clastic dykes from the Miocene lignites (Most Formation) in the North Bohemian Basin (Czech Republic). Of course, both of these compaction ratios do not correspond to the whole compaction of the peat/lignite seam after it was covered with mineral deposits (Text-fig. 5). In other words, the compaction ratio derived from clastic dykes is always smaller than the compaction ratio calculated for the entire coal/lignite seam.

## Stratigraphic methods

Stratigraphic methods are used to calculate the compaction ratio for peat beds and lignite seams only. This is due to the fact that the higher-rank coal seams are evidently deformed, inter alia, by post-depositional tectonic processes. Such deformations preclude the use of at least two of the three methods, the results of which are presented below and summarized in tabular form (Table 2).

Hurník (1972) used his own method, as shown in Figure 6, to calculate the compaction ratio for the above-mentioned Miocene lignites from the Most Formation in the North Bohemian Basin. In the case of these Czech lignites, the peat:lignite compaction ratios range from 3:1 to 6:1, averaging 4:1 (Table 2; Hurník 1972). This method has not been applied in the case of other lignite seams.

Hager *et al.* (1981) compared data from two pairs of boreholes from the Lower Rhine Basin in Germany (Text-fig. 7). They obtained an average value of the peat:lignite compaction ratios of 3:1 for the Rhenish Main Seam; however, the ratios range from 2.7:1 to 3.5:1 (Table 2; Hager *et al.* 1981; Hager 1993). Moreover, Kasiński (1984, 1985) employed the method proposed by Hager *et al.* (1981) for the Miocene lignites of the Ścinawa Formation in western Poland, calculating a peat:lignite compaction ratio between 1.7:1 and 2.9:1 (Table 2).

Using his own method, Widera (2002) and Widera *et al.* (2007) estimated the magnitude of the compaction process for two the middle Miocene lignite seams of the Ścinawa and Poznań formations in central Poland (Text-fig. 8). For the older Ścinawa Formation seam, the obtained peat:lignite compaction ratio is approximately 2.5:1. For the Poznań Formation coal the average value is equal to 2:1 (Table 2). This method, like the other ones belonging to the stratigraphic methods category, may be used under the following conditions: 1) post-depositional erosion of the mire and the lignite seam has not taken place; 2) post-depositional tectonic and/or glaciotectonic deformations are excluded; and 3) mineral intercalations in the lignite seam are absent (Widera 2002; Widera *et al.* 2007).

For the purposes of this study, compaction ratios for two other lignite/coal seams that fulfill the above-mentioned conditions were also calculated. On the basis of data presented by Markič and Sachsenhofer (1997, their text-figs 2, 4, and the text), the peat:lignite compaction ratio for the Pliocene Velenje lignite seam in Slovenia is about 2.1:1. This is very close to the result reported by Brezigar (1985/86), which is 2:1. Another example is the first application of this method to higher-rank coals belonging to the Pennsylvanian coal seams from

Illinois (USA). Using data on cross-sections, the compaction effects may be calculated (Nelson 1983, his text-fig. 41). In this case, the obtained peat:coal compaction ratio is approximately 7:1. However, this compaction ratio value is most often taken for subbituminous coals (Text-fig. 1; e.g. White 1986; Flores 2013).

Conceptually, the same approach was used for the Holocene coastal peats, for example, in the northeast USA and southwest Britain (Bloom 1964, his text-fig. 2 and Table 2; Haslett *et al.* 1998, their text-fig. 4). In these cases, the recalculated maximum peat:peat compaction ratios are 7.7:1 and 2.5:1 respectively (Text-fig. 1). Therefore, it should be noted that these compaction ratios are equal to or greater than those obtained for the lignite seams. This paradox will be discussed below.

## Paradox

Finally, at least one paradox emerged during the review of the methods of obtaining, and the results of, the peat:coal compaction ratio. This paradox refers to the fact that compaction ratio values are higher for peats than for lignites (Text-fig. 1).

The question arises of how it is possible that the compaction ratio for peat is greater than that obtained for lignite in the majority of examples. It appears that this can be explained by changes in the properties of the peat/lignite. The most important factors affecting the compaction are the duration of the development of the mire and the degree of decomposition of the organic matter. Most of the modern mires, for which the compaction has been extensively investigated, are younger than 10 ka (e.g. Bloom 1964; Haslett *et al.* 1998; Allen 2000; Bird *et al.* 2004; Long *et al.* 2006; Van Asselen *et al.* 2009; Van Asselen 2011). Thus, the plant matter in the mire beds is less decomposed than in the lignite seams. It has been estimated that the lignite seams were deposited over thousands of years (e.g. Kojima *et al.* 1998; Petersen *et al.* 2003), through tens or hundreds of thousands of years (Volkov 2003; Jerrett *et al.* 2011; Flores 2013), to as much as 7 Ma in the case of the lignites in the Lower Rhine Basin in northwest Germany (Schäfer *et al.* 2004, 2005). So, when the top layers of the peat were formed, the basal layers were already highly decomposed and dewatered; that is, (auto)compacted (Falini 1965; McCabe 1984; Volkov 2003). In fact, in the case of thick and long-standing mires, their basal layers may be characterized by physical and chemical properties typical of lignite for which the water content is less than 75% wt. and the calorific value is more than 6.5 MJ/kg.

A good example here is the Philippi mire in northeast Greece, which is regarded as the deepest contemporary mire in the world (Teichmüller 1968; Christanis 1998; Volkov 2003). The peat was accumulated between 0.7 Ma ago and the middle of the twentieth century, when the mires were drained for agricultural use (Christanis 1998). The mire is 190–200-m deep; however, its upper ~70 m is still in the stage of peat while the lower part of the sedimentary sequence has already passed into lignite (Teichmüller 1968; Volkov 2003).

After burial, therefore, the lower part of the mire may be only slightly subject to compaction. On the other hand, the upper layers of the mire may have a much larger magnitude of compaction similar to the above-mentioned modern mires. Thus, it seems evident that the peat:lignite compaction ratio may be sometimes lower than the peat:peat compaction ratio (Text-fig. 1). The compaction is ongoing and cumulative, such that lower part compacted early but still must be considered overall.

## CONCLUSIONS

This work is devoted to one of the most interesting and unsolved challenges of modern coal geology: the compaction of organic-rich sediments. Therefore, the main methods that allow us to estimate the amount of the peat:coal compaction ratio were reviewed while the greatest attention was paid to the compaction process during the transition of peat into lignite. The major conclusions are as follows:

There are many methods for calculating compaction ratios, which can be classified into four categories: density, inclusions, petrographic, and stratigraphic. Moreover, the first three categories can be combined as a group of indirect methods while the last category belongs to the group of direct methods.

Indirect methods allow us to calculate the compaction ratio for the constituents of the mire/coal seam or the relative size of compaction between them. Using these methods, however, the peat:coal compaction ratio for the entire coal seam cannot be determined directly. Obviously, the results achieved in this way can be converted and calibrated using other methods.

Only by means of direct methods, including the category of stratigraphic methods, are the geologically most reliable results provided. Obviously, the correctness of the calculated compaction ratio depends on compliance with designated assumptions that must be rigorously fulfilled. In other words, the compaction ratio should be calculated for each lignite seam separately.

In summary, it can be concluded that the majority of the peat:lignite compaction ratios obtained for various lignites range from 2:1 to 4:1. This means that the peat thickness prior to burial was 2–4-times greater than the currently observed thickness of the lignite seam. Therefore, the peat:lignite compaction ratios of the abovementioned interval, that is from 2:1 to 4:1, should be taken into account in a variety of geological research.

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