Some Remarks on the Most Glaciotectonically Deformed Lignite Deposits in the World – Sieniawa, Western Poland

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Abstract

In the area around the village of Sieniawa in western Poland, lignite has been exploited on an industrial scale for over 150 years. The deposits where mining is carried out, initially underground and now opencast, were strongly deformed glaciotectonically during the Pleistocene. The lignite seam in the exploited deposits creates numerous folds and thrusts/nappes, giving them complex geology. As a result, the lignite deposits in the vicinity of Sieniawa are considered the most disturbed of all the world's deposits still being mined.

Keywords: *Neogene lignite seam, Pleistocene glaciotectonics, Sieniawa Lignite Mine, Lubusz region, Polish Lowlands*

1. Introduction

Lignite still plays a key role in the Polish energy mix, although its share has fallen from ~35% to ~20% in recent decades [1-4]. However, lignite mined near Sieniawa in western Poland is not generally used for electricity generation, but for heating and agricultural purposes. In short, lignite is sold mainly to local customers for heating residential and industrial buildings, greenhouses, etc. The exception were the years 2019–2024, when the Sieniawa Lignite Mine sold relatively large amounts of lignite (>2 million tonnes – Mt) to the Konin Power Plant in central Poland [5, 6]. It is worth adding here that the average annual lignite production in this mine is in the range of 0.1–0.2 Mt, and in 2024 it exceeded 1.0 Mt [7].

The main aim of this study is to present the complex geology of the Sieniawa 1 and Sieniawa 2 deposits (Fig. 1), where lignite has been/is being mined in the last two decades. This aim will be achieved by showing the stratigraphic architecture of the exploited lignite seam both in the field (i.e., opencast mines) and in geological cross-sections. Additionally, the average direction of the Scandinavian ice sheets' advance onto the Sieniawa area will be given.

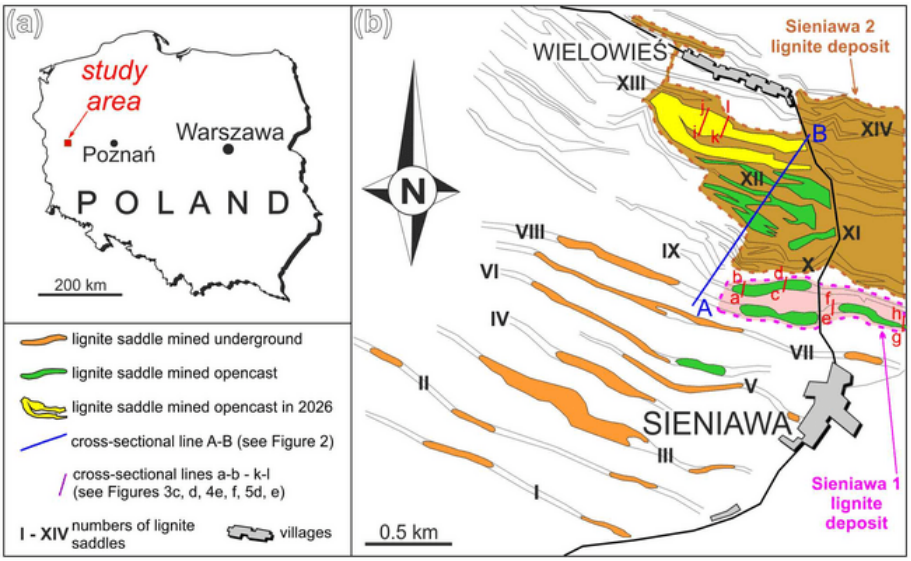

Fig. 1. Location map; (a) study area in the background of Poland; (b) mined lignite deposits Sieniawa 1 and Sieniawa 2; note the location of cross-sectional lines.

2. Materials and Methods

The results of field observations in the form of photographs presented in this article were obtained in the years 2010, 2015 and 2025. Fieldwork covered lignite opencast mines, called saddles by miners and geologists, with the subsequent numbers IX, XIII and XIII (Fig. 1b). The height of lignite walls rarely exceeded 10 m, while their width reached a maximum of 50 m. Generally, they are oriented in the SSW–NNE direction, i.e., approximately perpendicular to the extent of the lignite saddles.

Simplified geological cross-sections through the individual saddles were made in the same direction (SSW–NNE) and as close as possible to the lignite walls observed in the field (see Fig. 1b). Parallel to them, a geological cross-section A–B was drawn, which shows the geology of the area between the studied lignite saddles VIII and XIII (cf. Figures 1b and 2). All these cross-sections were prepared based on materials obtained from the geological archive of the Sieniawa Lignite Mine.

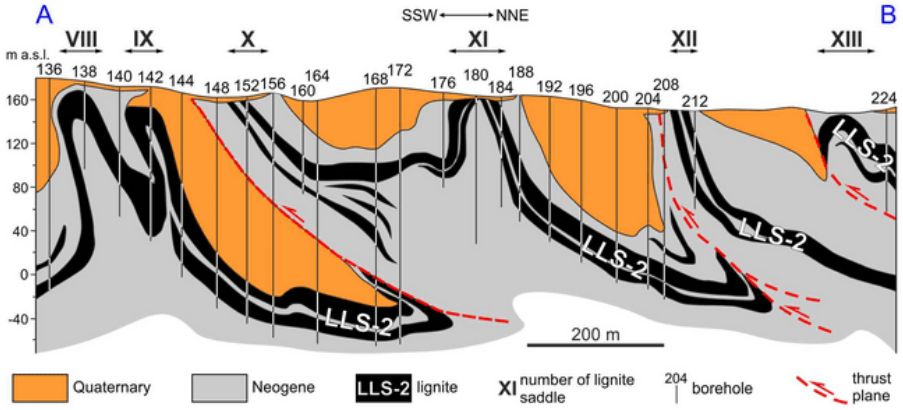

Fig. 2. Complex geology between lignite saddles VIII and XIII [9-11]; note strongly glaciotectonically disturbed lignite seam (LLS-2); for location of the cross-sectional line A–B see Figure 1a.

3. Geological Setting

In the study area, at a depth of ~160–180 m b.s.l., there is a sub-Cenozoic basement that is tectonically faulted. It is composed mainly of Cretaceous carbonate rocks such as marls and limestones. Above, the early Oligocene (Rupelian) sediments lie in the form of a continuous and undeformed layer of marine glauconite sands up to 80 m thick. The Paleogene is covered by Neogene and Quaternary sediments of very variable thickness [2, 7-11].

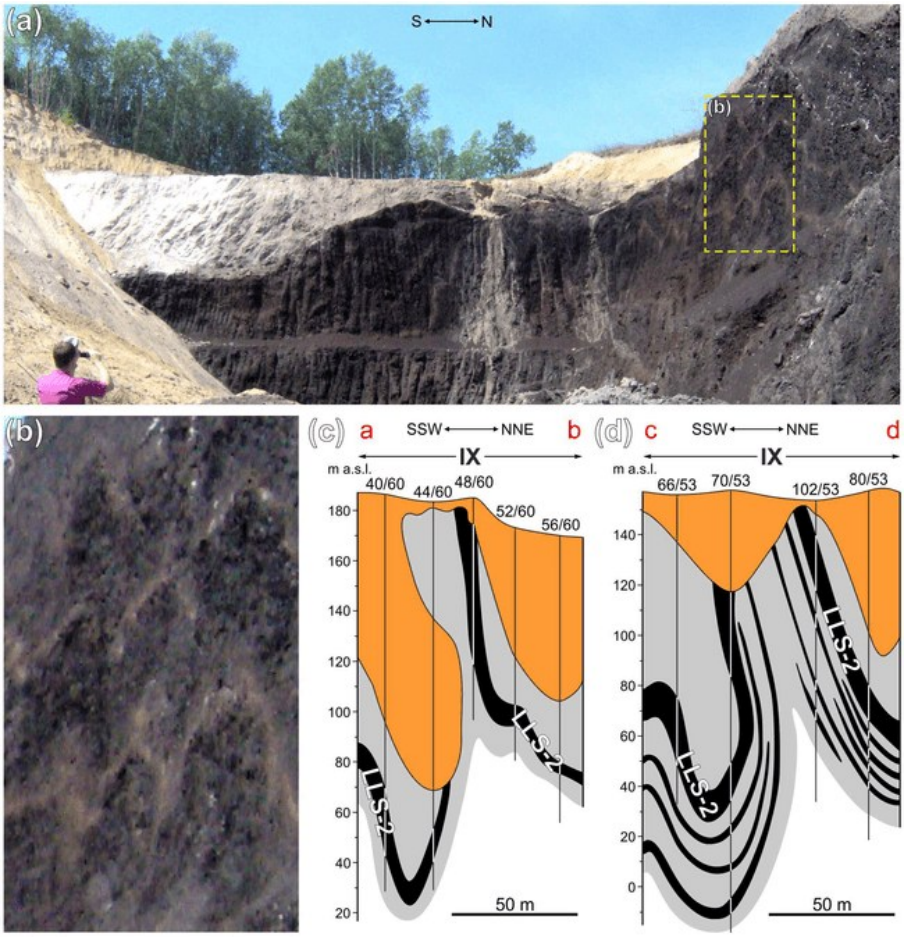

Fig. 3. Geology of the saddle IX in the Sieniawa 1 lignite deposit; (a) broad view of LLS-2; (b) close-up view depicting the strongly folded internal structure of LLS-2; (c), (d) cross-sections through the lignite saddle IX; for location of the cross-sectional lines a–b and c–d see Figure 1a, and for explanations see Figure 2.

The Neogene is up to 300 m thick and is composed mainly of terrestrial sediments. These are mainly sands, coaly sands and coaly muds, among which the 2nd Lusatian lignite seam (LLS-2) occurs in the upper part of the succession [8, 10]. This lignite seam

has been the subject of industrial mining in the Sieniawa area since 1872, for the first >100 years using the underground method and for the last nearly 50 years using the opencast method [7, 12-14] (see Figure 1b). The process of lignite exploitation in the study area was/is very difficult due to the deforming effects of the Scandinavian ice sheets in the Pleistocene. These glaciotectonic deformations in the form of folds and thrusts/nappes reach depths of up to 200–250 m, including LLS-2 (Figure 2; [11, 13, 15]). Hence, the Sieniawa 1 and Sieniawa 2 lignite deposits are genetically classified as glaciotectonic types [16] and are among the most glaciotectonically disturbed in the world [2, 7, 12, 17].

As the name suggests, LLS-2 is a continuation of the lignite seam found in the Lusatian region, in the easternmost part of Germany. Its age is determined at the latest Early Miocene–early Middle Miocene [2, 18]. LLS-2 exploited by the Sieniawa Lignite Mine is characterised by good chemical and technological parameters: the average net calorific value – 9–10 MJ/kg, ash yield – <9 wt% and sulphur content <0.9 wt%. On the other hand, based on the preliminary results of palynological studies, it can be concluded that LLS-2 (initially peat) from the examined deposits was accumulated in warm, close to subtropical climate conditions. Plant communities were then dominated by swamp forests and shrub bogs, surrounded by mesophilic forests. Furthermore, marine influences have so far been recorded palynologically only during the deposition of sub-lignite coaly muds [7].

4. Results

4.1 Saddle IX

Description: In 2010, the lignite saddle IX was available for direct field observations. In fact, these were the highest fragments of its anticlinal part, i.e., located above the groundwater level. The mined LLS-2 generally formed an upright fold at mesoscale (Figure 3a). However, internally it was more disturbed, as evidenced by the strongly deformed, light brown (pale) layers of weathered lignite lithotype (Figure 3b). On a macroscale, as seen in cross-sections a–b and c–d, LLS-2 forms upright, slightly asymmetric folds with an amplitude of >160 m. It should be noted, however, that their uppermost parts are truncated and the continuity of the lignite layers is interrupted (Figure 3a, b).

Interpretation: The above-described LLS-2 from the saddle IX is characterised by a simple structure on the macroscale and a much more deformed internal structure on the mesoscale. On the other hand, the lack of continuity of the lignite layers was certainly caused by Pleistocene post-sedimentary erosion [12, 13]. Therefore, it can be assumed that the folded geometry observed in the field was not created as a result of glaciotectonic folding, but as a result of erosion of the northern limb of the macro-fold visible in the geological cross-sections (cf. Figure 3a and 3c, d).

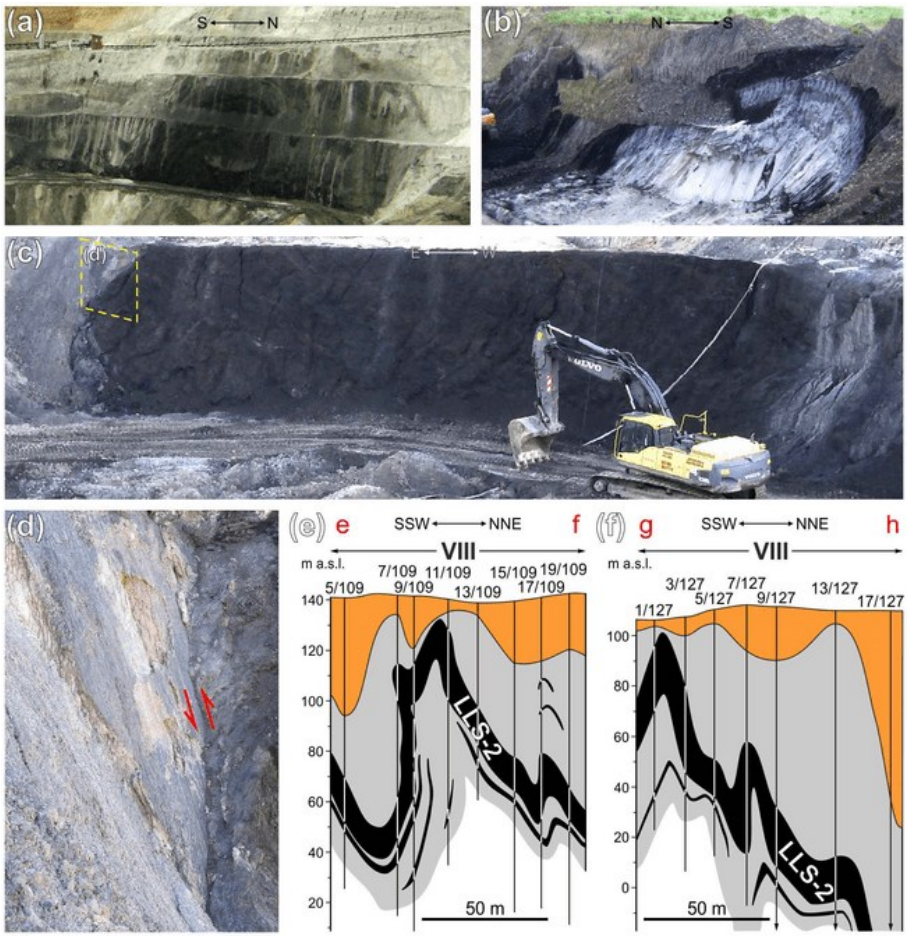

Fig. 4. Geology of the saddle VIII in the Sieniawa 1 lignite deposit; (a)–(c) broad view of LLS-2; (d) close-up view depicting the thrust surface; note the contact between the Pleistocene glacigenic sediments and LLS-2; (e), (f) cross-sections through the lignite saddle VIII; for location of the cross-sectional lines e–f and g–h see Figure 1a, and for explanations see Figure 2.

4.2 Saddle VIII

Description: Field observations carried out in 2015 on the saddle VIII provided extensive information on glaciotectonic deformations of both Neogene and Quaternary sediments [12]. However, this study focused solely on the deformation of Neogene

sediments. Unlike the saddle IX, here LLS-2 creates clearly visible folds. They are upright and symmetrical with or without exposed sub-lignite sands in the core (Figure 4a, b). In the opencast mine, it was also possible to document the contact of Quaternary sediments with the lignite seam (LLS-2) along the thrust surface (Figure 4c, d). Simplified geological cross-sections through the saddle VIII show the continuity of lignite layers and a slightly more diversified stratigraphic architecture of folds on a macroscale. This applies to the limbs of the major folds, within which secondary folds can be seen (Figure 4e, f).

Interpretation: The lignite saddle VIII, observed in the field, has a simple geometry in many places, with the highest parts of the anticlines preserved. However, it is interesting that the contact of LLS-2 with Quaternary sediments was documented in the opencast mine, which is not shown in the geological cross-sections a–f and g–h (cf. Figure 4a-d and 4e, f). In the case of the saddle VIII, the results of field observations partially confirm the information obtained from the borehole data – the lack of erosion of the hinge zones of the folds, and partially complement them – the thrust surface.

4.3 Saddle XIII

Description: In 2025, the part of the saddle XIII located above the groundwater level was available for field study (Figure 5a). The lignite wall was ~10 m high and ~40 wide, forming a standing (up-right) fold with its strongly disturbed internal structure (Figure 5b, c). The attached geological cross-sections, located very close and almost parallel to the mentioned lignite wall, show that the folds change geometry along the saddle XIII from upright and symmetrical to slightly inclined and asymmetrical (Figure 5d, e).

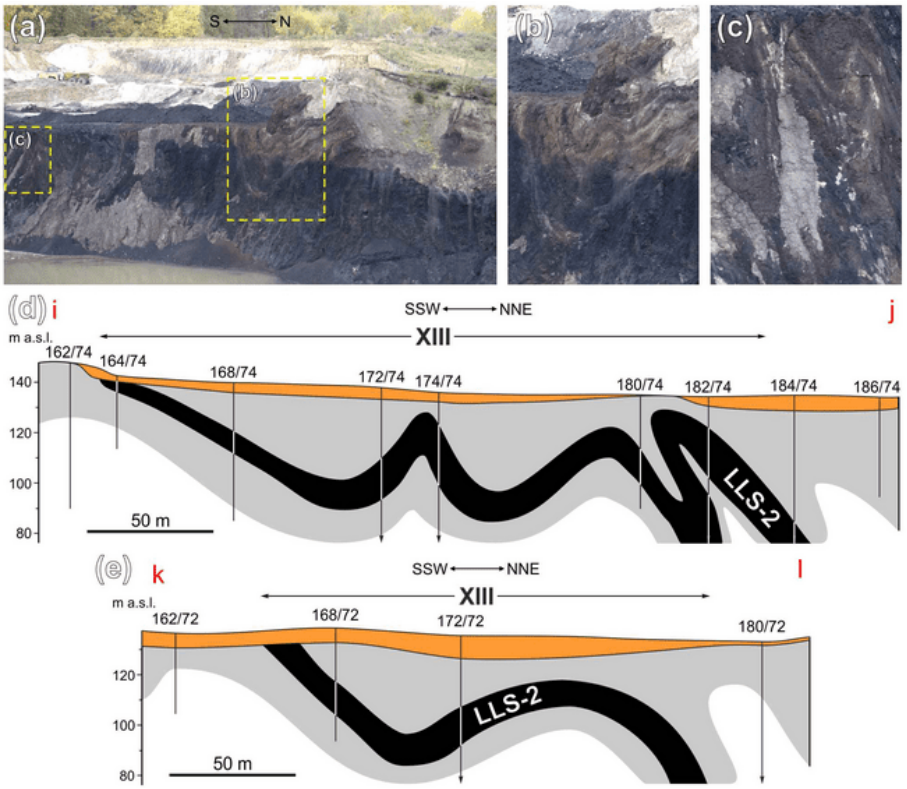

Fig. 5. Geology of the saddle XIII in the Sieniawa 2 lignite deposit; (a) broad view of LLS-2; (b), (c) close-up view depicting the strongly folded internal structure of LLS-2; (d), (e) cross-sections through the lignite saddle XIII; for location of the cross-sectional lines i–j and k–l see Figure 1a, and for explanations see Figure 2.

Interpretation: The part of LLS-2 visible in the field roughly corresponds to what is depicted in the cross-section i–j between boreholes 180/74 and 182/74 to the groundwater level, i.e., to a depth of ~120 m a.s.l. (cf. Figure 5a and 5d). Taking into account the internal structure, this fold, inclined on the macroscale, can be called a disharmonic fold on the mesoscale [7, 19]. A very similar situation was documented within all studied lignite saddles, especially within the saddles IX and XIII (cf. Figures 3b and 5b, c). In these cases, the strongly disturbed internal structure of the folds is highlighted by the presence of light brown (pale) layers of weathering lignite among other lithotypes with colours close to black.

4.4 Main direction of deformations

Assumption: There is a general consensus among researchers that the lignite deposits in the Sieniawa area were glaciotectonically deformed [2, 7, 9, 11, 15, 16]. Therefore, when reconstructing the direction of the ice sheet movement, the extension (elongation, strike) of glaciotectonic macrostructures, including folds and thrusts, is used. This approach is based on the fundamental assumption that the direction of movement of the Scandinavian ice sheet(s) is perpendicular to the course of the aforementioned glaciotectonic structures [20, 21].

Solution: The strike (elongation) of glaciotectonic structures in the Sieniawa vicinity was previously calculated by the author based on 50 measurements from fragments of the lignite saddles from VIII to XVI. The obtained results indicate that the ice sheet/s responsible for the strong deformation of, among others, the Sieniawa 1 and Sieniawa 2 lignite deposits moved from the azimuth 23° to 203°. In other words, the main forces disturbing the Cenozoic sediments around Sieniawa acted approximately in the NNE–SSW direction [12, 13].

5. Conclusion

Lignite deposits located in the Sieniawa region in western Poland are completely glaciotectonically disturbed. The exploited 2nd Lusatian lignite seam (LLS-2) of Early/Middle Miocene age is arranged in the form of numerous folds and thrust (nappes) called lignite saddles.

This paper compares the results of field studies and geological cross-sections through the saddles IX and VIII (Sieniawa 1 deposit) and saddle XIII (Sieniawa 2 deposit). Generally, glaciotectonic structures are dominated by standing (up-right) or inclined folds on a macroscale, while on a mesoscale they are disharmonic folds. Discontinuous structures in the form of thrust surfaces have also been documented both in the field and in geological cross-sections.

Currently, only in the vicinity of Sieniawa are glaciotectonic type of lignite deposits being exploited. Therefore, it seems fully justified to say that they are the most glaciotectonically deformed in the world, certainly among the lignite deposits discovered so far.

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