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The Piesberg: A NW-German site of international importance for the Pennsylvanian (Late Carboniferous)

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Abstract

Piesberg quarry is famous for its Upper Carboniferous plant and arthropod fossils, including several holotypes of flying insects. The high degree of maturity of the Piesberg strata, such as the presence of anthracitic coal, quartzite, and large quartz crystals, led to controversies over a possible underlying thermal anomaly. The Piesberg is of further importance for correlation between the deep underground of northwestern Germany and the Ruhr basin coal field, as well as the Pennsylvanian coal areas in North America, and for investigations of Upper Carboniferous tight gas fields. The importance of the Piesberg for international geosciences has been enabled through its very rich mining history beginning in the Middle Ages and its long scientific history beginning at the end of the 18th century. Today, the Piesberg is not only one of the largest active quarry sites in Europe, but also a local recreation and hiking area. While the Museum am Schölerberg in Osnabrück protects its paleontological heritage through ongoing excavations and houses the world's largest fossil and mineral collection from Piesberg, the UNESCO Global Geopark TERRA.vita and the city of Osnabrück conserve its geological heritage and promote environmental education through the Piesberg Cultural and Environmental Park. This paper highlights the international importance of the Piesberg by compiling its fossil record and paleoenvironmental interpretations. We also present preliminary data on new floral and faunal elements found in a recently discovered lake deposit. Further, the very rich mining history is briefly outlined and geoconservation and geotouristic measures are described.

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Introduction

Until 1898, the Piesberg quarry (Lower Saxony, NW Germany) was a black coal area mined for anthracitic coal and is now an active quarry site for quartzite used as building materials and road gravel (Harms 2019). The importance of the Piesberg as a recreation and environmental education site has increased in the past decades by the establishment of the Museum of Industrial Culture as well as hiking trails, information panels, viewing points, a mountain bike park, an arboretum, and by restoring protected historical mining buildings. Because of its importance in geosciences, in 2019 the Piesberg was designated as a National Geotope, the highest honor for geosites in Germany. The Piesberg is one of the most important geological and most visited geotouristic highlights in the UNESCO Global Geopark TERRA.vita (Fig. 1; Fischer 2020).

The Piesberg geological site is internationally known primarily because of its high and diverse fossil content of plants (around 55 species), insects (more than 25 species), and other arthropods from its Upper Carboniferous strata. The very good conservation of the Piesberg material has enabled the reconstruction of nearly all the organ taxa for individual plant species. In addition to meter-sized root organs and tree trunks from coal swamp trees such as *Sigillaria* and *Lepidodendron*, branching structures and foliage of these plants were found (Josten *et al.* 1984; Ganzelewski *et al.* 2008). The vegetation and regular succession of sandstones, claystones, and anthracitic coal seams were accumulated in a paralic basin during the Late Carboniferous, in which a braided river system, lakes and a swamp environment with fluctuating water levels were established (Wrede *et al.* 2019). A weak marine influence is only indicated by foraminifers recovered from around the topmost Itterbeck coal seam of the Piesberg site (Knauff *et al.* 1971).

Arthropod finds from the Piesberg contribute to the knowledge of the ontogeny and evolution of flying insects (Brauckmann & Herd 2002, 2005; Zessin 2006, 2008; Brauckmann *et al.* 2009, 2015; Aristov 2015; Kiesmüller *et al.* 2019) and other arthropod groups, such as myriapods, arachnids, and crustaceans. Finds of giant insects such as the palaeodictyopteran *Mazonopterum* and dragonflies belonging to the Meganeuridae as well as the up to two-meter-long myriapod *Arthropleura* testify to the gigantic growth of many arthropods during the Late Carboniferous at the Piesberg (Brauckmann & Herd 2002; Brauckmann *et al.* 2015; Dunlop *et al.* 2008; Wrede *et al.* 2019). Recent research has described arthropod larvae at different stages of ontogeny on the basis of which the life cycle of these organisms could be reconstructed (Haug *et al.* 2013; Nel *et al.* 2013; Hörnig *et al.* 2014; Kiesmüller *et al.* 2019).

In 2018, Upper Carboniferous shales were discovered at the Piesberg, whose sedimentary characteristics and floral and faunal elements indicate deposition in a lacustrine environment. This was the first time that a lake deposit was found at the Piesberg, which lacks the otherwise typical basal mire sediments (Leipner & Chellouche 2019). These newly discovered floral elements indicate dry hinterland conditions, and the fauna shows relative abundances that diverge from normal values.

Here, we present a review of the fossil record and preliminary results of the continuing excavations on the lake deposit. Many abandoned quarries and outcrops on the edge of the quarry are listed as natural monuments. The preservation, protection, and maintenance of the Piesberg geosites are safeguarded by cooperations among the city of Osnabrück, the county of Osnabrück, the quarry company GP Papenburg, the Natural History Museum (Museum am Schölerberg) in Osnabrück, the Natural Science Association of Osnabrück (Naturwissenschaftlicher Verein), and the UNESCO Global Geopark TERRA.vita. The Museum am Schölerberg in Osnabrück houses the largest collection of Piesberg fossils. The Piesberg Cultural and Environmental Park is a geotourism center with a mining history museum, a historic light railway, and

hiking trails with practical discovery stations and information panels (Fischer 2020).

Geological Setting

The Piesberg is a mountain close to the northern border of the city of Osnabrück and located in the center of the UNESCO Global Geopark TERRA. vita (Lower Saxony, NW Germany; Fig. 1). The Upper Carboniferous outcrops of the Piesberg quarry extend for about 2 km, which makes it one of the largest quarries in Europe. Located in the Lower Saxony basin, the Piesberg was uplifted as a W-E striking anticline during the Alpine Orogeny (Fig. 2). The eastern flank of the Piesberg is bordered by a NW-SE striking, east-dipping cross fault of up to 600 m of displacement. The Piesberg anticline is part of the Piesberg-Pyrmont axis, a series of left-stepping, en-echelon-linked anticlines at the southern edge of the Wiehen Mountains-Flexure (Drozdzewski & Dölling 2018).

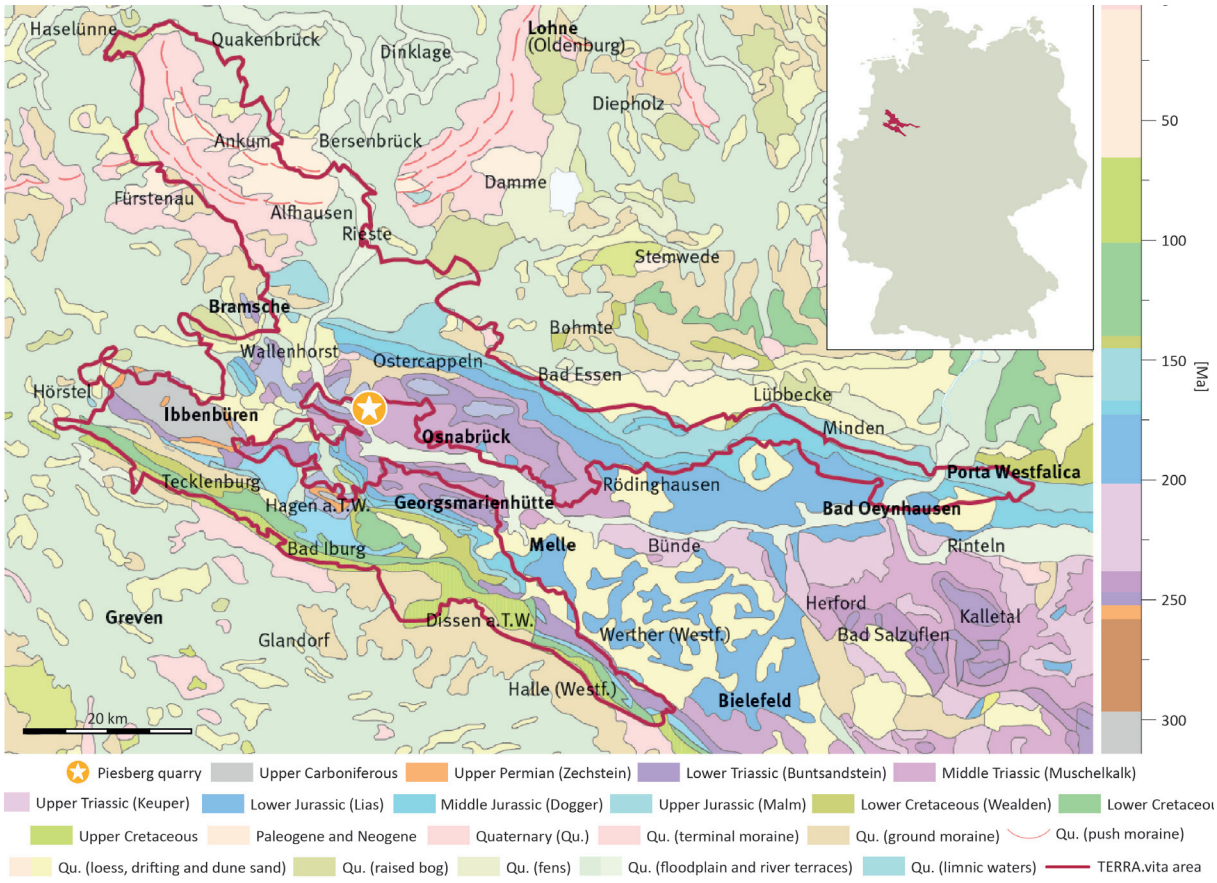

Figure 1. A geological map of the Piesberg Geopark area 1:1,000,000 showing the location of the Piesberg (geologic data from Toloczyki et al. 2006). The inset map indicates the location of the UNESCO Global Geopark TERRA. vita in Germany.

Together with the adjacent transpressional uplifts of the Schafberg (Ibbenbüren) and Hüggel (south of Osnabrück), the Piesberg constitutes the northernmost outcrop occurrence of Upper Carboniferous strata in Germany as part of the vast stretch of Variscan foreland basin-fill sediments of western and central Europe (Cleal *et al.* 2010). The Piesberg is surrounded by Mesozoic strata and is therefore up to 2,000 m higher than the surrounding lithostratigraphy (Fig. 2; Josten *et al*. 1984). The Carboniferous of the Osnabrück area comprises strata from Westphalian A to Westphalian D (c. 315-310 Ma; comprising parts of the Pennsylvanian in international stratigraphy). Therefore, the

Osnabrück area paved the way for the correlation of the Ruhr Basins in the south with the Carboniferous strata known from deep boreholes of northwestern Germany (Köwing & Rabitz 2005; Schuster 1971). The stratigraphic correlation of Westphalian C and D is mainly based on the comparison of fossil megaflora. The base of the Westphalian D is generally defined by the presence of the seed fern *Neuropteris ovata*. However, at the Piesberg and the nearby Schafberg in Ibbenbüren, this plant is usually found only in the upper parts of the sections. Microflora are poorly preserved because of the high level of coalification, so correlation of macro- and microflora is still problematic.

Within the quarry, about 100 m of Westphalian D are exposed. The sediments consist of more than 70% medium- to coarse-grained sandstones and conglomerates as well as subordinate siltstones and claystones, intercalated with coal seams (Fig. 2). These fluvial sediments were deposited by a braided river system with flow oriented to the north and west. Several 0.3 to 1.5-m-thick coal seams are intercalated with the accompanying flood-plain sediments. As a result of strong thermal heating, the sandstones show quartzitic cementation and the coal seams exhibit a high degree of maturity (anthracite). In 2018, an unusual, up to 1.5-m-thick lens of shaly mud and claystone was discovered in the western rock wall approximately 7 m above the *Mittel* coal seam; this is interpreted as an ancient lake sediment whose extent is not yet known. The fossil record of this palaeo-lake shows significant differences from the other fossil-bearing beds of the Piesberg.

The occurrences of up to 10-cm-diameter quartz crystals in fissures and of anthracitic coal at the Piesberg indicate an underlying thermal anomaly. Deposits at other locations in the region show similar high degrees of thermal maturity, which indicates heating of a larger area at depth (e.g., "black chalk" at Verthe, iron mineralization in Zechstein limestones at Hüggel and Schafberg, and Wealden anthracitic coal near Bohmte; Teichmüller & Teichmüller 1950; Klassen 2003; Lüders *et al.* 2012). The dating of the thermal event has been narrowed down to the Late Cretaceous (Stadler & Teichmüller 1971).

Three theories have emerged to explain this regional phenomenon. The oldest is based on geophysical measurements and describes the existence of a 7,500-km³ intrusive body at a depth of approximately 5 km – the Bramsche pluton (e.g., Reich 1927; Stadler & Teichmüller 1971; Klassen 2003). A more recent theory questions the existence of the Bramsche pluton and postulates that the entire area subsided to a depth of 7 km before it was tectonically inverted during the Alpine Orogeny (Senglaub *et al.* 2005, 2006; Adriasola-Muñoz 2007; Adriasola-Muñoz *et al.* 2007; Brink 2013; Bruns *et al.* 2013; Bruns & Littke 2015). The most recent theory favors hydrothermal fluids ascending along large-scale faults of a fault shatter-zone tens to hundreds of meters wide, and the heat transport caused a thermal anomaly at least at the kilometer scale (Will *et al.* 2016; Wüstefeld *et al*. 2017a, b).

The Piesberg :A Site of International Importance for Late Carboniferous Flora and Fauna

The following sections comprise published and unpublished observations of the diverse Piesberg flora and fauna. We have placed our emphasis more on the fauna than the flora, because in the last years the fauna has been more intensely investigated.

Flora of the Coal Mires

Over 99% of the fossil record from the Piesberg constitutes plants and plant remains, often fragmented. The typical flora of the coal seams consists of lycopsids (up to 40 m tall), such as *Lepidodendron* and *Sigillaria* (Fig. 3A). Especially above the Zweibänke coal seam, there are occasional upright stems and rooting organs of lycopsids in situ with a quartzitic sandstone filling and dispersed marcasite/pyrite. From the other coal seams of the Piesberg locality, such in situ plant

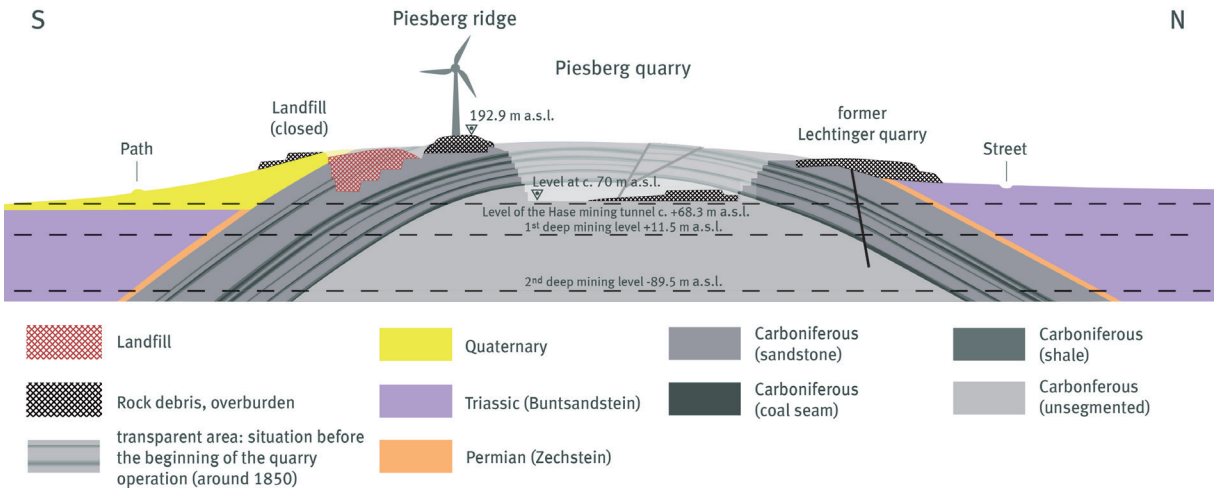

Figure 2. Superelevated geological cross-section (S-N) of the Piesberg (modified from Haarmann 1911).

finds have been extremely rare and mostly exhibit mudstone fillings. A nice example of these *Stigmaria*-rooting organs is displayed at the Museum am Schölerberg, Osnabrück, and was found in 1886 as the coal was extracted by deep mining. Fossilized specimens up to 30 m tall of *Cordaites*, a primitive horsetail with *Cordaianthus* cones, were also found. *Calamites* grew up to 10 m and had large rhizomes. Small in situ horsetail stems are scarce at the Zweibänke coal seam. Sphenophyllaceans, related to the calamite horsetails, probably formed a low-lying scrambling type of vegetation (Fig. 3B). Pteridosperms were very common, seed-bearing (e.g., the seed *Trigonocarpus*), fern-like plants. Their morphology varied from small trees to scrambling creepers and they include many morphogenera (e.g., *Neuropteris*, *Alethopteris*, *Eusphenopteris*, *Mariopteris*). True spore-bearing ferns were common, most of them tree-ferns. The most common fossils of true ferns from the Piesberg are fronds belonging to *Pecopteris*. Small fragments of charcoal are occasionally present in the shales above the Johannisstein coal seam as well as in the newly discovered lake deposit. It seems likely that the charcoal originated from floras affected by paleo-wildfires in the dryer hinterland.

Indirect evidence of arthropod-plant interactions was observed on plant remains. Leaf-margin feeding is evidenced mostly on leaves from the pteridosperm *Macroneuropteris scheuchzeri*, as are rare traces of surface-feeding. Oviposition marks on calamitalean stems are not very uncommon (Béthoux *et al.* 2004; Wolterbeek 2014), but rarely seen on other plants. A new type of arthropod boring in calamitalean stems was recently described from the Piesberg site (Laaß *et al.* 2020). Rare occurrences of egg clutches on leaves are currently under investigation.

Fauna of the Coal Mires

Schultka (1988) showed that faunal elements are not as rare in the shales as had been assumed and that the assumption that plant-fossil rich shales contained very few faunal elements also seemed to be incorrect. But it was not until the turn of the millennium that a continuous and long-term systematic search for faunal elements was initiated by the amateur paleontologist Michael Sowiak, who systematically searched all shale layers for animal fossils.

His finds led to the conclusion that faunal elements are not as rare as thought. However, in the most commonly searched beds, with a high amount of silt particles and large fronds of ferns and seed ferns, faunal elements are indeed very rare. The finer-grained shales, which contain large amounts of plant debris and fewer more complete plant

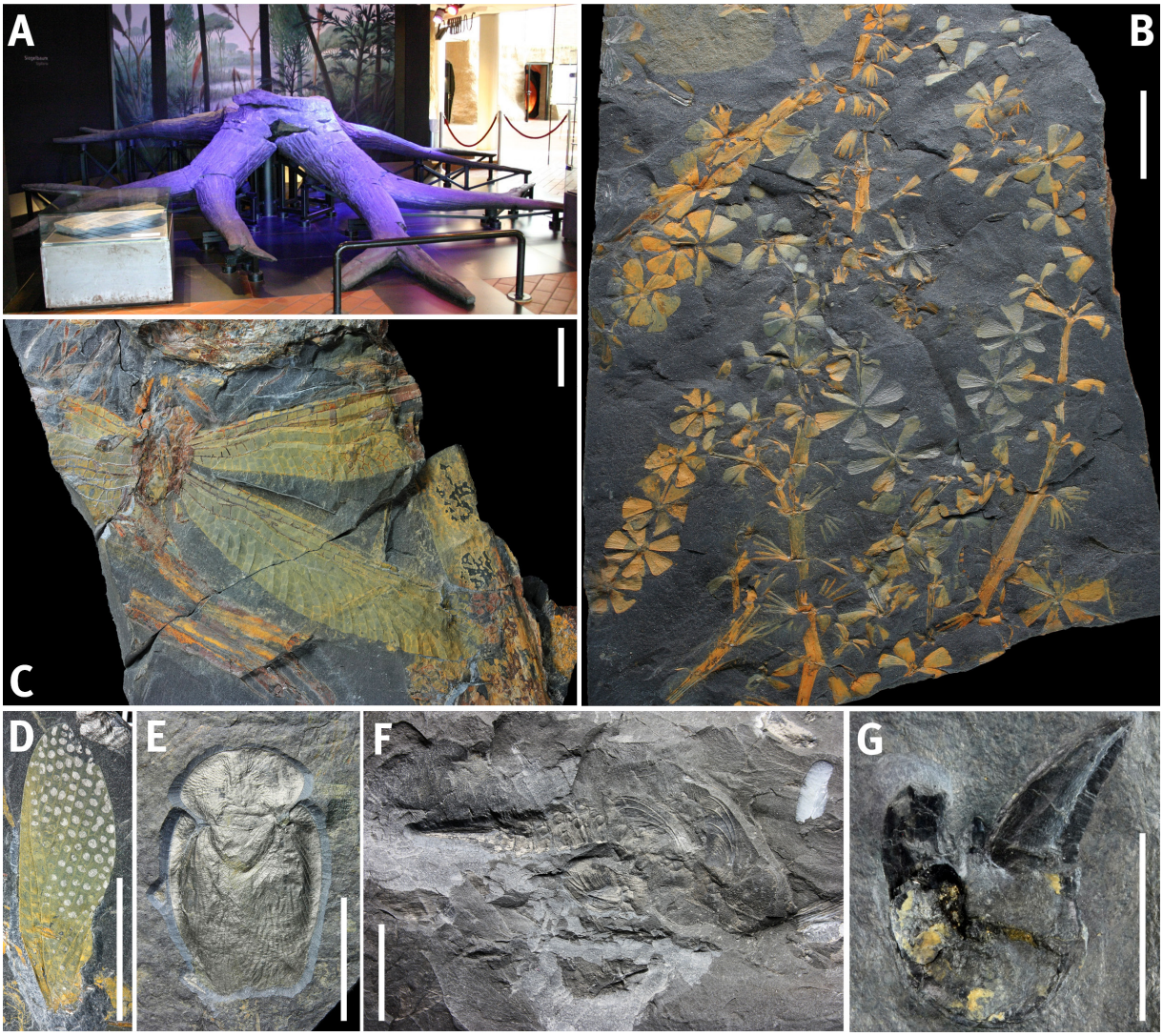

Figure 3. Examples of fossil finds at the Piesberg in the collection of the *Museum am Schölerberg*, Osnabrück (all scale bars equal 10 mm, photographic credits belong to the *Museum am Schölerberg*). A) *Stigmaria* root organ and stem of *Sigillaria* sp. discovered at the top of the *Zweibänke* coal seam in 1886 and displayed in the entrance hall of the *Museum am Schölerberg*. B) *Sphenophyllum emarginatum*, top of the *Zweibänke* coal seam (collection no. MAS Pal 661, finder: Michael Sowiak). C) meganisopterid dragonfly, top of the *Zweibänke* coal seam (collection no. MAS Pal 1110, finder: Stephan Brauner). D) Archaeorthopterid flying insect, top of the *Zweibänke* coal seam (collection no. MAS Pal 1389). E) Mylacrid cockroach *s. l.*, lake sediment layer 4. F) *Rochdalia*-type nymph, top of the *Dreibänke* coal seam (collection no. MAS Pal 1242; compare with Kiesmüller *et al.* 2019). G) tricuspid tooth of the freshwater shark *Orthacanthus*, lake sediment layer 4.

fossils, also contain relatively more common fragmentary animal remains; there are rarely more complete fossils. This work has provided a broad spectrum of fossil fauna for scientific research – an example of the importance of the work of amateur paleontologists to the scientific community.

The most common animal fossils are microconchids and evidence that they formed colonies on plant remains and faunal elements, even on insect wings. The second most common animal remains belong to xiphosurans (primarily *Euproops; Liomesaspis* are extremely rare) and freshwater bivalves (*Anthraconaia*). Haug et al.

(2012) identified ten different ontogenetic stages of the xiphosuran *Euproops* from Piesberg quarry, ranging from small larvae to adult animals, which showed significant development of the opisthosomal epimera. Freshwater bivalves predominantly belong to *Anthraconaia pruvosti*, while *A. piesbergensis* is represented by only a few specimens (Eagar *et al.* 1998, 1999).

The most abundant insects from the Piesberg locality, represented by adults as well as nymphs, belong to Blattodea sensu lato, comprising more than 60% of insects (Wrede *et al.* 2019) with at least two genera. The Blattodea, in general, have not yet been thoroughly investigated with the exception of some nymphs, including some of the smallest Paleozoic roachoid nymphs (Haug et al. 2013; Hörnig et al. 2014).

Other Paleozoic insect groups from Piesberg are Palaeodictyoptera, Megasecoptera, Odonatoptera, and Neoptera, based on 1,400 specimens. Most of the remains are isolated wings, wing fragments, and fragments of different ontogenetic nymphal stages, though some more complete insects and nymphs have been found as well, accounting for up to 3% of insect remains (Brauckmann & Herd 2002, 2005, 2007; Béthoux & Herd 2009; Brauckmann et al. 2009, 2015; Aristov 2015; Pecharová et al. 2021).

One of the giant insects described from Piesberg and typical of the Late Carboniferous is the palaeodictyopteran *Mazonopterum* with a wingspan of approximately 37 cm. Brauckmann et al. (2015) showed close paleobiogeographic relations between three localities in Germany (Osnabrück, Lower Saxony; Ibbenbüren, North Rhine-Westfalia, and Ludweiler, Saarland) and Mazon Creek, Illinois, USA. The biogeographical record of *Mazonopterum wolfforum* supports a close paleogeographic Euramerican connection during the Late Carboniferous. Exceptionally well-preserved palaeodictyopteran nymphs of the *Rochdalia*-type (Fig. 3F), some with large ovipositors, were found in the roof shales of the Dreibänke seam (Kiesmüller *et al.* 2019).

The Odonatoptera from Piesberg are currently under investigation by Zessin *et al*. (in press). These range from tiny dragonflies with wingspans of about 5 cm to meganeurids with a wingspan of over 30 cm (Fig. 3C–D). About ten odonatopteran species, including the two published species (Brauckmann 1983; Zessin 2006), can be distinguished. In the coming years, more new species and first occurrences at the site can be expected as a result of more detailed study of the numerous existing Piesberg insect collections together with new finds.

Remains of the myriapod *Arthropleura armata* were mostly found in the roof shales of the Zweibänke seam. Spiders are rare. The most abundant arachnid is the trigonotarbid *Aphantomartus pustulatus* (Rössler 1998). The true spider *Arthrolycosa* is less common. The Phalangiotarbidae are only known from two specimens. Scorpion remains are extremely rare. Dunlop *et al.* (2008) described the first known, nearly complete scorpion from the Piesberg. For a long time, this was the only find, further specimens only being recovered in recent years.

Crustaceans (excluding conchostracans) are extremely rare. Pygocephalomorpha and Syncaridae have been documented, the latter being known only from the lake deposit. The Pygocephalomorpha have been described by Pazinato et al. (2019). Conchostraca are extremely rare in the roof shales of the coal seams but highly abundant in the lake deposit. Ostracods were described by Braun (1997) while extracting arthropod cuticles with hydrofluoric acid from coal seam roof shales. Macroscopic identification of ostracods has not been successful to date.

Fish remains are very rare; mostly scales and parts of scale envelopes of actinopterygians and rhizodontid rhipidistians have been found. Shark

remains are only represented by rare egg capsules (three genera and five species). The most common genus is *Palaeoxyris* (about 70%); a few examples of *Fayolia* and very few samples of *Vetacapsula* have been found to date.

Fossils from the Newly Discovered Lake Deposit
An approximately 1.5-m-thick lens of partly shaly mud- and claystones has been discovered in the western rock wall approximately 7 m above the Mittel coal seam, thinning out towards the south and north. The shale succession consists of at least five beds of varying grain sizes with finely laminated to platy stratification, which is in part easily fissile. The succession is capped by a weakly to non-stratified, silty mudstone, which probably represents crevasse-splay sediments.

The shale lens differs from the typical mudstone beds above the coal seams of the Piesberg by its clear signs of rhythmic deposition, with couplets of darker laminae intercalated with broader, light grey layers of varying thicknesses. The lack of current marks on the bedding planes points to a depositional depth below storm-wave base. At the base of the succession, a sandstone can be observed replacing the typical coal seam and correspondingly displacing mire sedimentation. According to Leipner & Chellouche (2019) the lens is an ancient lake sediment whose extent is not yet known.

The fossil records of this paleo-lake exhibit significant differences to the other fossil-bearing beds of the Piesberg. Plant fossils from the lake deposit are often better preserved than the flora from the coal mires of the Piesberg and offer better possibility for identification down to the species level (e.g., in the case of *Pecopteris* finds). Alongside more typical flora of Pennsylvanian mires, representatives of dryer habitats, although rare, have been identified (i.e., part of a large frond of *Taeniopteris* sp. and a frond of *Dichophyllum moorei*). The specimen of *Dichophyllum moorei*, part of a hinterland floral association, is to date the stratigraphically oldest record of this species worldwide. The newly discovered lake shales have already produced several fossil liverwort specimens that demand closer investigation. Another, as yet undescribed, bivalve species occurs in the newly discovered lake deposit, sometimes covered by potential gastropod egg clutches. In addition, two genera of freshwater syncarid malacostracans represent the first record of this group from the Piesberg and complement the, as yet, underrepresented crustaceans from the locality (Leipner & Chellouche 2019).

Fossil insects from the Piesberg are primarily preserved as isolated wings, wing fragments, and disarticulated nymphal remains, with only 1 to 3% being more complete imagos and nymphal specimens. In the lake deposit, a larger number of articulated insect specimens, with a frequency of around triple the presence in the mires, has been recorded. Small, isolated wings, in particular, occur more often than elsewhere in the Piesberg, although larger wings are less common. The smallest isolated insect wing ever found at the Piesberg quarry, with a length of only about 6 mm, was from the lake sediments. A shift in the abundance of xiphosurans is also observable in the Piesberg lake sediments: *Euproops* have been less common and the small xiphosuran *Liomesaspis* are found in much larger numbers than in the rest of the quarry.

It is noteworthy that during two years of excavation of the lake deposit, about 45 scorpion remains have been found, while in 30 years of collecting in roof shales above coal seams of the Piesberg only two scorpion remains were recovered. Specimens of spinicaudatan conchostracans are very common in the lake deposit and represent at least three species (Leipner & Chellouche 2019). This is a further example of significant differences in fossil abundance between lake and mire sediments of the Piesberg.

In the same horizons in which egg capsules of chondrichthyans were found, teeth (Fig. 3G) and fin spines of chondrichthyans also occur infre-

quently. Osteichthyan remains include single palaeonisciform scales and parts of articulated scale envelopes as well as single scales of rhizodontids. Acanthodians are represented by incomplete remains. Specimens of teeth and fin spines are not merely preserved as impressions but in full-body, three-dimensional form and support the hypothesis that the ancient freshwater lake had a lower pH than the mire deposits and, therefore, phosphatic elements such as bone, teeth, and scales had a far greater preservation potential when deposited in the paleo-lake than they would have had in the characteristically high pH of mire waters.

The Piesberg: Structural Change from a Black Coal Field to a Recreation Area

The following sections describe the rich mining history of the Piesberg, the conservation of the paleontological and geological heritage, and the establishment of the Piesberg Cultural and Environmental Park as a recreation area.

Mining History

The Piesberg has played an economically and culturally significant role in the Osnabrück region for the better part of 800 years. Eleven named coal seams outcrop or are known from boreholes, of which four have been exploited to variable extents up to as recently as the 1950s. The Piesberg has a history of intensive quarrying, exploiting its natural resources of anthracitic black coal and quartzitic sandstone.

The earliest traces of active mining at the Piesberg stem from the Neolithic Funnelbeaker culture. Blocks of Piesberg quartzitic sandstone, up to 3.7 m x 2.2 m x 0.8 m, were quarried and used in the building of the megalithic Karlsteine tomb, which was constructed around 5,500 to 4,800 BP (Wulf & Schlüter 2000; Fansa 2009; Bußmann 2017). As early as the 12th century, limonitic iron ore extracted from surface trenches (Pingen) was used in smelters at the western base of the Piesberg (Haarmann 1911). Beginning in the mid 15th century, black coal was mined from coal seams outcropping at the Piesberg. Under exclusive mining concessions obtained by the city of Osnabrück in 1568, the first mine shafts were sunk for underground extraction of one of the shallower coal seams (the Johannisstein seam).

It was not until 1830 that further mining shafts and adits reached deeper coal seams, such as the Mittel, Zweibänke, and Dreibänke seams. Deep mining below groundwater level started in 1868 with the sinking of the Hase shaft, which coincidentally marked the decline of black coal mining operations at the Piesberg following recurrent flooding of shafts and tunnels by CO_2-rich groundwater. Mining problems culminated in 1893, when nine miners were killed in the 210-m-deep Stüve shaft by a sudden inrush of groundwater and release of CO_2. After months-long strikes of miners and other staff protesting against poor working conditions and unfavorable new work rules, mining of black coal finally stopped in 1898. Black coal mining at the Piesberg was reactivated for a short while during the early 1950s owing to the general scarceness of energy resources after World War II (Müller 1896; Fricke 1954; Hollmann *et al.* 1971; Hakenberg 1976; Köwing & Rabitz 1981; Josten *et al.* 1984; Eberhard 2008).

Large-scale extraction of quartzitic sandstones from the Piesberg quarry started in 1859 and evolved into one of the largest sandstone quarry complexes in central Europe (Josten *et al.* 1984). Sandstones and accessory mudstones continue to be quarried from the Piesberg; 2018 alone saw an annual production of approximately one million metric tonnes (Josten *et al.* 1984; Harms 2019). The volume of usable rock will provide material for the next 15 to 20 years, after which large areas in the quarry will be permanently protected and preserved as geological sites (Harms 2019). Recent analyses have shown that the Piesberg Carboniferous sandstones are an analogue outcrop for a better understanding of tight gas reservoirs, especially for the sub-surface in northern Germany (Bruns *et al.* 2013; Wüstefeld *et al.* 2017a).

Preservation of the Palaeontological Heritage

Fossil collecting for scientific purposes began in 1799, when the famous mineralogist Dietrich Gustav Ludwig Karsten produced the first geological description of the Piesberg (Karsten 1799). In 1893, mining engineer Leo Cremer utilized plant fossils to correlate the geological strata of the Piesberg with other Carboniferous outcrops in western Germany (Cremer 1895). From these early beginnings, scientific work, mainly on the structural geology, sedimentology and paleobiota of the Piesberg strata, has continued intermittently until the present.

By far the largest collection of Upper Carboniferous fossils from the Piesberg locality is housed at the Museum am Schölerberg, Osnabrück. Among thousands of specimens, the collection includes samples of 22 possibly endemic species with 17 holotypes of extinct plants and animals, such as the palaeodictyopterid net-winged insect *Breyeria bistrata*, the archaeorthopterid *Forfexala kiarae*, and the meganisopterid dragonfly *Erasipterella piesbergensis* (e.g., Brauckmann 1983, 1995; Béthoux & Herd 2009). Further, the collection includes exquisitely preserved pieces of the giant myriapod *Arthropleura armata*, early roachoids (Fig. 3E) such as *Archimylacris* and mylacrids, and the earliest representative of the seed fern species *Dichophyllum moorei*. In addition, fossils of horseshoe crabs (*Euproops* sp.), ferns, seed ferns, arborescent lycopsids, and early gymnosperms (*Cordaites*) are safeguarded in the museum.

The museum collection consists of formerly private collections of museum associates, bequests of private collectors and researchers as well as specimens obtained by excavations organized by the museum and the Natural Science Association of Osnabrück. These excavations, aided by the association and its members (Michael Sowiak and Angelika Leipner) and other volunteers, have been ongoing for the better part of 30 years and have yielded many of the most scientifically relevant fossils.

The most impressive fossil find in the museum collections, on display in its entrance hall, is a rare, mostly complete and three-dimensional preserved root organ (*Stigmaria*) of the arborescent clubmoss *Sigillaria*. At 3.6 t, a diameter of 6.5 m, and a height of 1.5 m (Fig. 3A), it consists of the central stem and four dichotomizing root structures. Only three specimens of *Stigmaria* root organs have ever been recovered in Germany, all three from the Piesberg locality. One other specimen is on display at the German Mining Museum (Deutsches Bergbau-Museum) in Bochum. The third was on display at the Bergakademie Berlin, today part of the Technical University of Berlin, but was destroyed in a bombing raid during World War II (Thomas & Seyfullah 2015). Secondary public collections of Piesberg fossils are housed at the Ruhr Museum Essen, the IGP TU Clausthal, and the Museum Wuppertal amongst others.

The Piesberg Cultural and Environmental Park: A Tool for Geoconservation and Legal Protection

The UNESCO Global Geopark TERRA.vita and the city of Osnabrück have maintained the Piesberg Cultural and Environmental Park around the quarry since the 2000s. The heart of the park is an 8-km-long loop trail that leads visitors along numerous outcrops, including the light railway cut (Fig. 4E), the Lechtinger quarry, and medieval mining trenches (Pingen). Numerous information panels and discovery sites inform visitors about the geology and mining history along the trail (Fig. 4D). Three large wind turbines on the Piesberg ridge have become its landmarks (Fig. 4B). The tower stump of a smaller, older wind turbine was converted into a viewing platform in 2011 (Fig. 4C). Two additional viewing platforms offer spectacular views of the active quarry and the surrounding landscape. Further highlights of the Piesberg Cultural and Environmental Park include a mountain bike park and an arboretum. The latter was established around 1900 and displays exotic trees such as giant sequoia (protected as a natural monument), dawn redwood, ginkgo, monkey puzzle tree, and tulip tree.

Figure 4. Geosites at the Piesberg. A-B) Northeastern rock wall in the active Piesberg quarry, recognized as a National Geotope in 2019 (photos: Natur- und Geopark TERRA.vita). C) View of the publicly accessible viewing tower on top of the quarry ridge and the active quarry (photo: city of Osnabrück). D) The Johannissteine geosite, protected as a natural heritage, and a TERRA.vita information panel. The panel stands are relicts of the historical railway (photo: Natur- und Geopark TERRA.vita). E) The light railway cut exposes a coal seam and quartzitic sandstones. The light railway was re-enabled for geotourism by the Light Railway Piesberg Osnabrück Association (photo: Natur- und Geopark TERRA.vita). F) The megalithic Karlsteine tomb, constructed 5,500 to 4,800 years .(ago (photo: Hartwig Wachsmann

The intention of the Piesberg Cultural and Environmental Park was not only to create a recreation area and to promote environmental education, but also to serve to protect and conserve the geological sites in the area. Therefore, it has had the protective status of a landscape conservation area since 2019. Parts of the Piesberg area are also subject to the EU Habitats Directive. The northeastern quarry rock wall was recognized as a National Geotope in 2019 (Fig. 4A), the highest honor for geosites in Germany. Many of the geological sites at Piesberg, such as the Johannissteine and the megalithic Karlsteine tomb (Fig. 4F), are protected by Preservation Orders (Fischer 2020). Since 2020, grazing goats have kept the geological sites free of overgrowing vegetation.

The numerous mining buildings from the 19th century, such as the Piesberg Society House and the train station, are protected as historic monuments. The Museum of Industrial Culture has been housed in the former Hase shaft building since 1994 and exhibits machines from the early era of industrial mining at Piesberg. In addition, a 280-m-long mining gallery is accessible to visitors in the museum. The former pump house has been in use as a locomotive shed by the Piesberg Light Railway Association of Osnabrück since 2009. Tourists can travel with the Piesberg historical light railway for a distance of 1.2 km. The route will be extended by 1.3 km and will provide further TERRA.vita information panels by July 2021. The Stüve shaft building is currently being restored by a local association.

Conclusion

The Upper Carboniferous strata of the Piesberg have been of economic mining interest since the Middle Ages. While surface mining trenches testify to medieval coal mining, the numerous protected historical buildings at the Piesberg reflect early industrialization in the region. Today, the Piesberg is one of the largest hard rock quarries in Europe, reflecting the shift of economic interest to the mining of quartzitic sandstone for road gravel and building material.

Centuries of mining have provided a unique window into the environment and paleoecology of the Late Carboniferous of Central Europe and paved the way for more than two centuries of geoscientific activities at the site. The Piesberg is the type locality for many Upper Carboniferous plant and insect fossils, which has been made possible only by decades of fieldwork and collections by the Museum am Schölerberg and the Natural History Association of Osnabrück. While previous investigations of the Piesberg's lithological characteristics and fossil record indicate a swampy environment with fluctuating water levels and a braided river system during the Late Carboniferous, recently discovered shales add for the first time a lacustrine environment without a mire precursor stage. Preliminary interpretations of the plant fossils suggest dry hinterland conditions. However, excavations on these newly discovered lake sediments are still ongoing. The genesis of the high rock maturity is also currently controversial. Thus, even after more than 200 years of scientific research, the Piesberg still provides incentives for new theories.

The UNESCO Global Geopark TERRA.vita and the city of Osnabrück in close cooperation with the Museum of Industrial Culture, the Piesberg Light Railway Association of Osnabrück and the county of Osnabrück preserve the geological and mining heritage of the Piesberg by maintaining the Piesberg Cultural and Environmental Park for geotourism and other touristic fields as well as by legal protection and by rural conservation measures (e.g., goat grazing).

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Conflict of Interest

The authors declare that there is no conflict of interest in their work.

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