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# Structure of the 7 Ma Bükkábrány fossil forest in Hungary

**Abstract** An *in situ* late Miocene (Pannonian) fossil forest preserved as wood has been uncovered at Bükkábrány, Hungary. Excavation within the open-pit mine revealed 16 stumps that ranged from 1.8 to 3.6 m in diameter at the base and up to 6 m in height preserved atop a 16 m thick coal seam. A relative change in the elevation of Lake Pannon appears to have drowned the forest about 7 Ma ago. Sand deposited as part of a prograding delta covered the landscape and preserved the trunks in a waterlogged condition. Forest stand density was 36 stems per hectare. The trees grew 3 to 16 m apart. Their diameter at breast height ranged from 137 to 248 cm. Stem basal area varied from 3.46 to 8.44 $m^2$ per tree, yielding a forest basal area of 240 $m^2$/ha. The tree height was probably 44 to 52 m and the stem volume ranged from 44 to 125 $m^3$. The total biomass of 1400 t/ha is estimated for the Miocene Bükkábrány forest. The net annual primary production was in the range of 2.8 t/ha.

## Introduction

The upper Miocene lignite deposits are a major source of energy for countries such as Slovakia, Hungary, Austria, Bosnia-Herzegovina, and Serbia, which are located in the Pannonian Basin. Extensive open-pit mining occurs throughout this region and accounts for about 5% of the world's lignite production (Bechtel et al., 2007). The coal deposits formed along the shores of Lake Pannon while being infilled by river deltas during the late Miocene.

While coal mining has been going on for decades in theis region (Csilling et al., 1985), there has been little geological information published, and most of the geological information that is available is preserved in company files and archival reports.

In the Bükkábrány open pit mine in Hungary a fossil forest was discovered and excavated in the summer of 2007 (Fig. 1)(Kázmér, 2008). The trees have been identified as two extinct Cupressaceae species (Erdei et al., 2009). Their preservation is excellent and mostly preserved as unmineralized wood, displaying varying degrees of cellulose loss (Hámor-Vidó et al., 2009). This paper offers an overview of further new results and describes the studies that are in progress at this locality. Observations on trees, forest structure, embedding sediment, preservation, and mineralization are provided and illustrated. Finally, a brief summary of the forest structure is provided here.

## Methods

The trees were mapped by the geodetic service of the mine. The circumference at the base, at breast height, and at the top of each stump were measured using a tape measure. Calculation of tree height, stem volume, biomass, and productivity followed the forest mensuration methods as summarized in Williams (2007). The map of the fossil forest and measurement data of the individual tree stumps allow me to produce parameters used for characterizing forest structure: tree diameter,

**Fig. 1** Eight of the sixteen taxodiaceous trunks excavated in the Bükkábrány coal mine. The stumps are 4 to 6 m in height and are rooted on the Miocene coal. Photograph by J. Veres.

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basal area, height, volume, dominant, subdominant and suppressed individuals, age/diameter relationships, trunk density, annual wood production, aboveground biomass (Mosbrugger et al., 1994; Pole, 1999), and a centennial trend of $CO_2$-sequestration under a greenhouse climate (Osborne & Beerling, 2002).

Whether the recent and Miocene forest structures are the same, or there are any differences caused by evolution (Pregitzer et al., 2000), can be jointly answered with leaf flora analysis of L. Hably and E. Erdei and by pollen analysis of E. Magyari, both in progress.

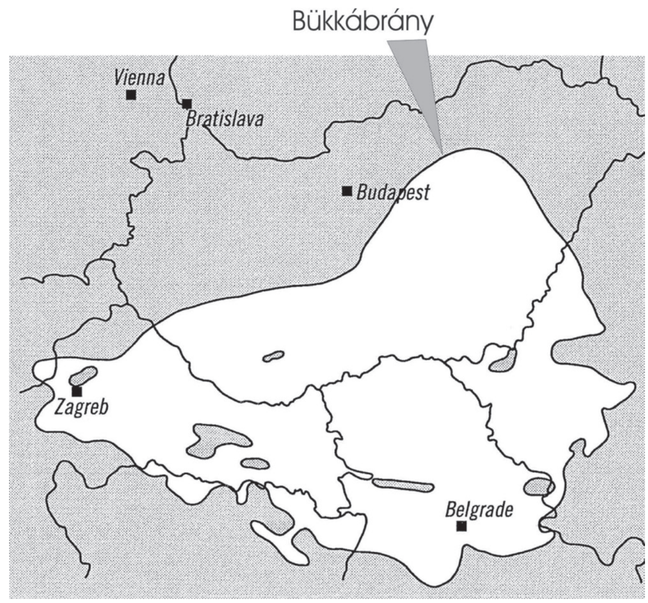


**Fig. 2** Location of the Bükkábrány at the northern margin of Lake Pannon (white) duruing the late Miocene, surrounded by land (shaded) (Magyar et al., 1999).

## Stratigraphy

The arcuate Carpathian Range surrounded Lake Pannon at the end of the Miocene. Rapidly emerging and eroding mountains supplied abundant sand—carried by large rivers from NW and NE to enormous deltas that filled parts of the lake. During the late Miocene (Pannonian) the shoreline was located just south of the Bükk Mountains (Magyar et al., 1999)(Fig. 2). A delta-plain forest produced enough organic matter to accumulate in marshes, which formed the coal seams when buried by sediments. Open-pit mines at Visonta and Bükkábrány mine this coal.

Neither the lignite nor the overlying sands contain any fossils suitable for precise age determination. Correlation with well-dated borehole successions via seismic profiles is in progress, indicating an age ranging from 6.9 to 7.2 million years (Magyar in Császár et al., 2009).

## Significance of the tree fossils

*In situ* fossil forests are those where the trees are preserved in growth position, and where the original forest structure is preserved.

Fossil forests of various geological ages have been found on all continents. In most cases, the wood is mineralized, turned to silica or carbonate, rarely to pyrite. Forests preserved as wood are extremely rare. Arctic Canada yielded several Paleocene (Williams et al., 2009) and middle Eocene forests (Williams et al., 2003b). There are mummified, fallen logs and upright stumps up to 0.5 m tall (Francis, 1991). Miocene forests from the western Arctic in Canada have yielded a rich fossil flora composed of mummified stumps, logs, and seed cones (Williams et al., 2008). The fossil forest of Dunarobba in the Italian Apennines is slightly mineralized, despite being only 2 million years old (Ambrosetti et al., 1995; Anonymous, 2000).

Erect, silicified, or calcified trunks are known from all continents and from most geological ages (Vadász, 1963). However, it is rare to find such huge trees, in life

**Fig. 3** Organic-rich foreset beds at the toe of a sandy delta front. The top of the coal bed is located in the foreground. Photograph courtesy of Bükkábrány Mine, Ltd.

position that are preserved as wood. The Bükkábrány Fossil Forest is probably the oldest fossil forest where large woody trees are preserved *in situ* and preserving the original forest structure.

### Burial and preservation

Sixteen tree trunks stood up to 6 m in height and up to 2 m in DBH and grew atop a 12 m thick lignite bed that is embedded by sand. The trees are preserved as mummifications (Hámor-Vidó et al., 2009). A complex process of degradation, burial, and diagenesis is outlined here. Seven million years ago, mature trees 400 to 1000 years in age grew in a marsh. Some show evidence of heart rot disease, while others show plant-insect and plant-animal interactions. Toppled trees—arranged more or less in parallel—suggest storm damage due to high winds. A 20 m rise in the water level of Lake Pannon drowned the forest. Evidence for a climate-induced rise in lake level (Harzhauser et al., 2008) and co-seismic base-level change (Kázmér, 2010) will be discussed elsewhere.

The 12 m thick lignite bed is overlain by grey sand. It consists of well-sorted, fine to medium-grained sand, lacking certain grain-size fractions. Kilometer-long exposures of the mine walls display this well-bedded sand. Immediately above the lignite bed containing the *in situ* forest the sand becomes horizontally bedded. Stratification is accentuated by layers of organic debris (Fig. 3) and pebble strings. These features suggest deposition in a lake bottom and a toe-of-slope environment.

**Fig. 4** Herringbone cross-bedding of delta plain sand located about 25 m above the coal seam.

An approximately 20 m thick set of 15 degrees north-dipping, parallel sand beds occur up section (Fig. 3). These foresets are typical of those encountered in a delta environment and are overlain by small-scale cross-bedded sand deposited in a delta plain (Fig. 4). Rare, centimeter-thick lignite beds were deposited in the inter-distributary marshes.

The sand surrounding the trees is grey and extends to a height of approximately 6 m above the coal and bases of the tree stumps. Upward the sand becomes less reducing and more oxic as indicated by the yellow and brown sand. The boundary of the grey and yellow sand coincides with the top of tree trunks (Fig. 5).

We suggest that a rapid rise of ca. 20 m in the water

**Fig. 5** Preserved portion of tree trunks embedded in grey sand, which is indicative of reducing conditions. Oxidizing conditions prevail in the area above the line. The line in the image indicates the approximate stratigraphic level that delineates the lower anoxic portion of the formation where the tree stumps are preserved and the upper oxic portion of the formation where there are no plant parts preserved.

level of adjacent Lake Pannon drowned the forest 7 million years ago. Sand transported by rivers flowing into the lake entombed the stems and filled the hollows and cavities within the stems. For seven million years the environment remained saturated and oxygen free.

As the water level rose relative to the shoreline, the increased accommodation space was filled by rapidly deposited delta sands that rapidly buried the forest (Kázmér, 2008). The activities of the anaerobic bacteria degraded the wood through removal of cellulose (soft rot)(Hámor-Vidó et al., 2009; Fig. 6). Delta foresets and bottomset beds enclose leaf litter accumulations that contain leaves, cones, bark, and wood fragments. Open cavities were filled with sand. Further sediment loading—of which only 60 m of thickness is preserved today—compressed both the organic accumulations (leaf litter mats) and trees. Originally circular cross-section of ths stems embedded in the marsh sapropel show approximately 90% compression. Erect trees embedded in sand suffered relatively minor deformation. A small amount of shortening resulted from small-scale normal faulting (centimeter scale movement), tilted towards the pith of the trees, and the development of subhorizontal folds within the woody tissue. Principal stress (sigma one) was vertical, i.e., produced by overburden. The root zone has been sheared along decimeter-scale normal faults.

Sulphur released from marsh sediments and iron-compounds dissolved in groundwater interacted to produce pyrite mineralization within the heartrot cavities, open fissures in the tree stems, and as scattered crystals that grew within the wood. Conspicuously, pyrite did not infiltrate the cellular structure, but overgrew preexisting folds and faults. Additionally, pyrite-cemented sandstone is attached to the exterior of the trees in irregular forms.

**Fig. 6** Fragments of sapwood that curled rapidly when exposed to sunshine, suggesting low cellulose content.

Uplift of the adjacent Bükk Mountains during the last two million years contributed to the erosion of a potentially significant part of the overburden. Exposure to direct sunlight and drying result in significant deformation, cracking, and disintegration of the wood tissue due to shrinkage and collapse of the wood cell structure (Kázmér, 2008).

## Forest ecology

### 1. The trees

*Taxonomy*

There are studies available on the leaf and pollen flora of Bükkábrány (Pálfalvi, 1952). The fossil trees have long been known from this and other nearby localities that are considered to be *Sequioxylon* (Pálfalvi & Rákosi, 1979) and *Taxodium* (e.g., Kordos & Begun, 2002). The initial anatomical studies of the freshly recovered wood facilitate the taxonomic identification of six of the trunks. These *Taxodioxylon germanicum* (Greguss) van der Burgh stumps are related to modern *Sequoia* Endlicher and *Glyptostroboxylon* Conwentz emend. Dolezych & Van der Burgh. The uppermost layer of the coal yielded abundant foliage and cones of *Glyptostrobus europaeus* (Erdei et al., 2008; Császár et al., 2009). Additionally, previous studies reported leaves of *Alnus*, *Ulmus*, and an extinct broad-leaf shrub, *Byttneriophyllum* from locations a few kilometers away (e.g., Hably, 1992). The pollen assemblage from the lignite attests to a species-rich swamp and riparian forests dominated by members of Taxodiaceae (Erdei et al., 2008). Taxonomic identification of the remaining trees, and those found as isolated remains, is in progress.

*Trunk morphology*

The trees bear a conical buttress reaching up to 3 m elevation or more above the ground surface. Buttresses are without any bark and bear sharp ribbing similar to those of the giant redwood (*Sequoiadendron*) (Fig. 7). The ribs enclose bark pockets, reaching deep into the base of the tree (Fig. 8).

### 2. The forest

*Stand density*

A 45 × 100 m E-W rectangle encloses all the trees (Fig. 9). Sixteen erect trees plus one well-preserved large, *in* *situ* root is found in this area. The trees are distributed unevenly, with large treeless spaces, (e.g., a 20 × 30 m rectangle) in the middle of the *in situ* stump layer. We are certain that there were no more large trees within the excavated area. Careful removal of all overburden and paleosoil by heavy scrapers allowed observation of the forest floor. A 20 × 20 m triangular area in the southeastern corner (less than 5% of the plot) might have additional trees, but this area remains unexcavated. The 4500 $m^2$ plot contains 17 trees (16 stems + 1 root ball); this allows for a calculation of 38 stems per hectare, a low value compared to other fossil forests, suggesting that the individual trees were of an exceptionally large size and hence widely spaced. The trees were spaced from 3 to 16 m apart with an average distance between the closest trees of 8 m (13 measurements).

**Fig. 7** Heavily ribbed stump. Photograph by I. Dunkl.

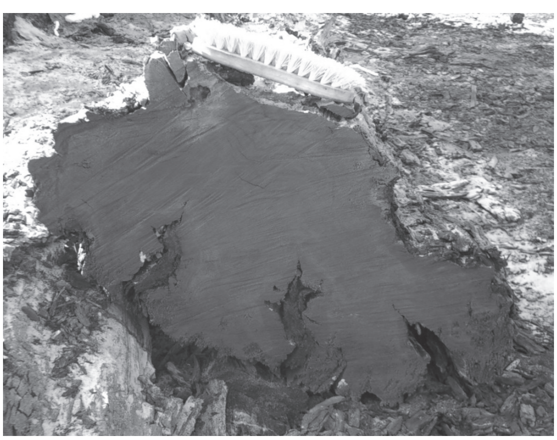

**Fig. 8** Deep bark pockets visible in transverse section. Brush for scale is 20 cm long.

*Diameter and basal area*

Seven trees were measured to obtain diameter at breast height (DBH) and basal area measurements. The other trees were partially buried and not excavated down to forest floor, leaving the lower parts of stumps unavailable for measurement. The DBH of the trunks ranged from 137 to 248 cm, with an average of 193 cm. The basal area of the individual stems range from 3.46 to 8.44 $m^2$, with an average of 6.35 $m^2$, yielding a basal diameter of 240 $m^2$/ha.

*Tree height*

There are a large variety of equations available for estimation of tree height from tree diameter. The Bükkábrány trees are probably close relatives of *Glyptostrobus*. The closest marsh-dwelling taxon for which extensive forest mensuration literature exists is the genus *Taxodium*. The best results are supplied by species-specific equations, which have recently been developed for *Taxodium* (Parresol et al., 1987; Parresol, 1992). Unfortunately, these are based on stem diameter measured above the basal swelling of *Taxodium*, at 3 m above the ground. Also, the data were measured on second-growth trees that were less than 200 years old. Because our measurements at the time of excavation were mostly diameter at breast height (DBH), the interspecific allometric technique (Niklas, 1994) was used to determined the maximum tree height from the DBH measurements. This method exploits the generally high correlation of stem height with stem diameter. Tree heights of 44 to 52 m are calculated; a height that is

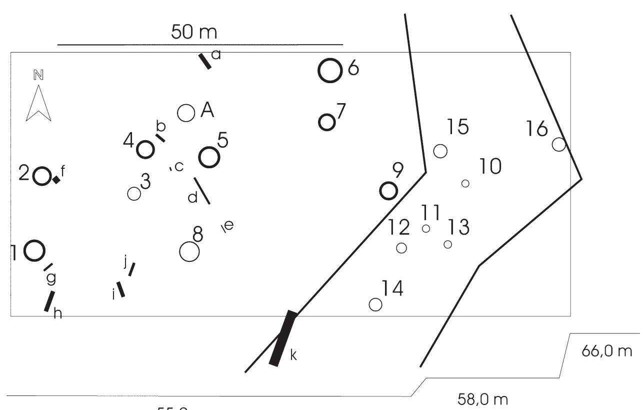



**Fig. 9** Structure of the excavated Bükkábrány forest. The circles are proportional to the trunk diameter at ground level. Heavy lines indicate work walls in July 2007. Short lines are coarse woody debris. Map courtesy of Bükkábrány Mine, Ltd.

not unusual considering the height of other redwoods such as *Sequoia* and the Eocene *Metasequoia* trees from Axel Heiberg Island that were up to 40 m tall. However, one should keep in mind that the general allometric equation presented by Niklas (1994) produces the greatest estimate of fossil tree height that probably represent the upper boundary of the actual average tree height in this forest.

*Stem volume, biomass and productivity*

The volume of wood contained in a fossil stem was estimated based on a parabolic model (Creber & Francis, 1999) and ranged from 44 to 125 $m^3$. These values are used to derive estimates of aboveground biomass, when wood density is assessed from closest living relatives (*Sequoia* and *Glyptostrobus*). Decay and cellulose loss from the wood (Hámor-Vidó et al., 2009) prevent accurate measurement of fossil wood density. A minimum oven-dry density value of 0.46 $g/cm^3$ (as measured for the related *Sequoiadendron*: Kennedy, 1973) provides an aboveground stem biomass ranging from 20.1 to 57.6 metric tons. Given that about 84% of tree biomass is contained in the stem and 16% in the crown (as calculated for the related *Metasequoia*: Williams et al., 2003a), a total biomass of the individual trees ranges from 23.9 to 68.6 ton. A truly high value of 1400 t/ha total dry biomass is estimated for the Miocene Bükkábrány forest. With an average ring width of 0.3 mm, annual net primary production was in the range of 2.8 t/ha.

## Comparison with Cenozoic fossil forests

Table 1 lists a number of Cenozoic age *in situ* fossil forests. Bükkábrány is at a similar paleolatitude as the somewhat younger Pliocene Italian forests and probably had a similar climate (group B). The taxonomic composition, diameter, tree height, and stand density are all similar to one another.

Group C comprises the other Canadian fossil forests that grew in the polar latitudes. A colder climate compared to that experienced during the Miocene in Hungary and more frequent disturbance resulted in a polar forest composed of smaller diameter trees, but at a much higher stand density.

The high aboveground biomass (1400 t/ha) is probabaly due to the age and size of the trees at Bükkábrány (estimated 400 to 1000 years old).

## Conclusions

The late Miocene Bükkábrány fossil forest was preserved by catastrophic flooding along the shore of Lake Pannon and subsequent burial by sand being deposited by a prograding delta. Continuous burial of the wood in a low-oxygen environment over the last 7 Ma has resulted in superb preservation. Being buried in low oxygen conditions for 7 Ma it is preserved as wood. The forest consists of two genera (*Taxodioxylon* and *Glyptostroboxylon*) that are related to modern

**Table 1** Comparison of forest mensuration parameters of select Cenozoic, *in situ* fossil forests. The older the forest the lower its position in the table. The data collected from two modern forests are provided for comparison. — A: modern forests, B: temperate fossil forests, C: polar fossil forests.

| | Locality (Reference) | Location | Latitude/ paleolatitude | Age | Dominant taxa | Stand density (trees/ha) | Basal area ($m^2$/ha) | Mean diameter (cm) | Tree height range (m) | Aboveground biomass (t/ha) |
|---|---|---|---|---|---|---|---|---|---|---|
| A | Tanashi A plantation (Williams et al. 2003a) | central Japan | 35°N | Recent | *Metasequoia glyptostroboides* | 816 | 81 | 34 | 31 | 358 |
| | Ea Ho (Averyanov et al. 2009) | Vietnam | 13°N | Recent | *Glyptostrobus pensilis* | 456 | | 63 | 13 | |
| B | Dunarobba (Ambrosetti et al. 1995) | Italy | 42.5°N | Plio-Pleistocene | *Glyptostrobus* sp. | 43 | | 150–250 | 31–35 | |
| | Stura di Lanzo (Martinetto & Farina 2005) | Italy | 45°N | Pliocene | *Glyptostrobus europaeus* | | | 178 | | |
| | Bükkábrány (this paper) | Hungary | 48°N | late Miocene | Taxodiaceae | 38 | 240 | 193 | 44–52 | 1400 |
| C | Banks Island (Williams et al. 2008) | Arctic Canada | 74°N | middle Miocene | Pinaceae | 650 | 116 | 24 | 21 | 259 |
| | Axel Heiberg (Williams et al. 2003b) | Arctic Canada | 75°–85°N | middle Eocene | Taxodiaceae | 396 | 30 | 23 | 23–27 | 76 |
| | Axel Heiberg (Williams et al. 2003b) | Arctic Canada | 75°–85°N | middle Eocene | Taxodiaceae | 127 | 117 | 35/19 | 37–43 | 644 |
| | Ellesmere Island (Williams et al. 2009) | Arctic Canada | 75°–80°N | late Paleocene | Taxodiaceae | 300 | | 76 | 32–36 | 576 |

*Sequoia*. The Bükkábrány fossil forest was probably mature and even-aged. Sixteen erect tree trunks stand up to 6 m in height and are preserved over a one-half hectare area. Stand density is low compared to other *in situ* fossil forests with a stem density of 38 stems per hectare and basal area of 240 $m^2$/ha. Calculated tree height was 44 to 52 m, and biomass (including the crown) was 1400 t/ha, a high value compared to other fossil forests. The Miocene Bükkábrány fossil forest consisted of even-aged, old trees in a mature community.

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