THE LATE TRIASSIC *ARAUCARIOXYLON ARIZONICUM* TREES OF THE PETRIFIED FOREST NATIONAL PARK, ARIZONA, USA

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ABSTRACT. Examination and measurement of many of the trunks attributed to *Araucarioxylon arizonicum* Knowlton eroded from the Late Triassic Chinle Formation in the Petrified Forest National Park, Arizona demonstrate that the living tree did not closely resemble any of the present-day *Araucaria* trees of the southern hemisphere as postulated in past reconstructions. The research indicates that it was a tall monopodial tree with branches occurring in a disordered manner on the trunk from the base to the crown. Calculations using the allometric method of Niklas indicate that the trees were of considerable size. The largest recorded trunk has a basal diameter of nearly 3 m and may represent a tree 59 m high, when living. The root system of the *A. arizonicum* tree consisted of a ring of four to six steeply inclined lateral roots and a massive, vertically directed tap root. Many of the trunks still have their root systems attached, a circumstance that indicates their felling by the cut-bank operations of the local river system. The massive roots of these trunks, particularly the large tap root, are consistent with growth in soft, deep, alluvial soil, and the thin scale bark is to be expected in a tropical climate free from frost.

RECONSTRUCTION of fossil vascular plants is often difficult and the results are frequently open to question because their organs typically separate shortly after death of the parent plant, prior to burial. Furthermore, only a few specimens of a particular fossil species are usually available as a database. Thus, an unprecedented opportunity for the preparation of a reconstruction of a Late Triassic conifer exists in the Petrified Forest National Park, Arizona, USA (Text-fig. 1) where thousands of virtually uncompressed fossilized trunks of the *Araucarioxylon arizonicum* Knowlton (1889) tree with attached root and branch bases are preserved (Pls 1–4). Here we attempt a reconstruction of the *A. arizonicum* tree, the dominant plant megafossil in the park as well as the dominating plant in the flora (Andrews 1961).

DESCRIPTION OF STUDY AREA

The Petrified Forest National Park covers an area of *c*. 37,700 hectares (93,500 acres) in east-central Arizona near the southern boundary of the Colorado Plateau Province (Text-fig. 1). At many places in the Park, the desert surface is strewn with the large trunks of extinct gymnospermous trees that have been eroded out of the Chinle Formation and remain from forests existing in the region during the Late Triassic (Carnian–Norian). The majority consist of silicified secondary wood of the conifer species *A. arizonicum* (Pl. 1, figs 1–4). Also present, but in much smaller numbers, are the trunks of two other gymnospermous trees not described in this paper.

The Chinle Formation covers a large area in the Colorado Plateau Province of the south-western United States and extends from north-eastern Utah to east-central Arizona and from southern Nevada into central New Mexico. It was deposited in a large basin located along the western edge of Pangaea at a palaeolatitude of *c*. 15–18° N (Dubois 1964; Smith *et al.* 1981) in a variety of non-marine environments. These environments included fluvial channels, crevasse-splays, lacustrine basins, deltas and marshes, and flood plains (Demko 1995).

In east-central Arizona the Chinle Formation has a thickness of *c*. 400 m and consists mostly of brightly coloured sandstones and mudstones together with minor amounts of conglomerate, dark highly organic shale, and paper coal. A few thin beds of white to pink, freshwater limestone occur near the top of the unit

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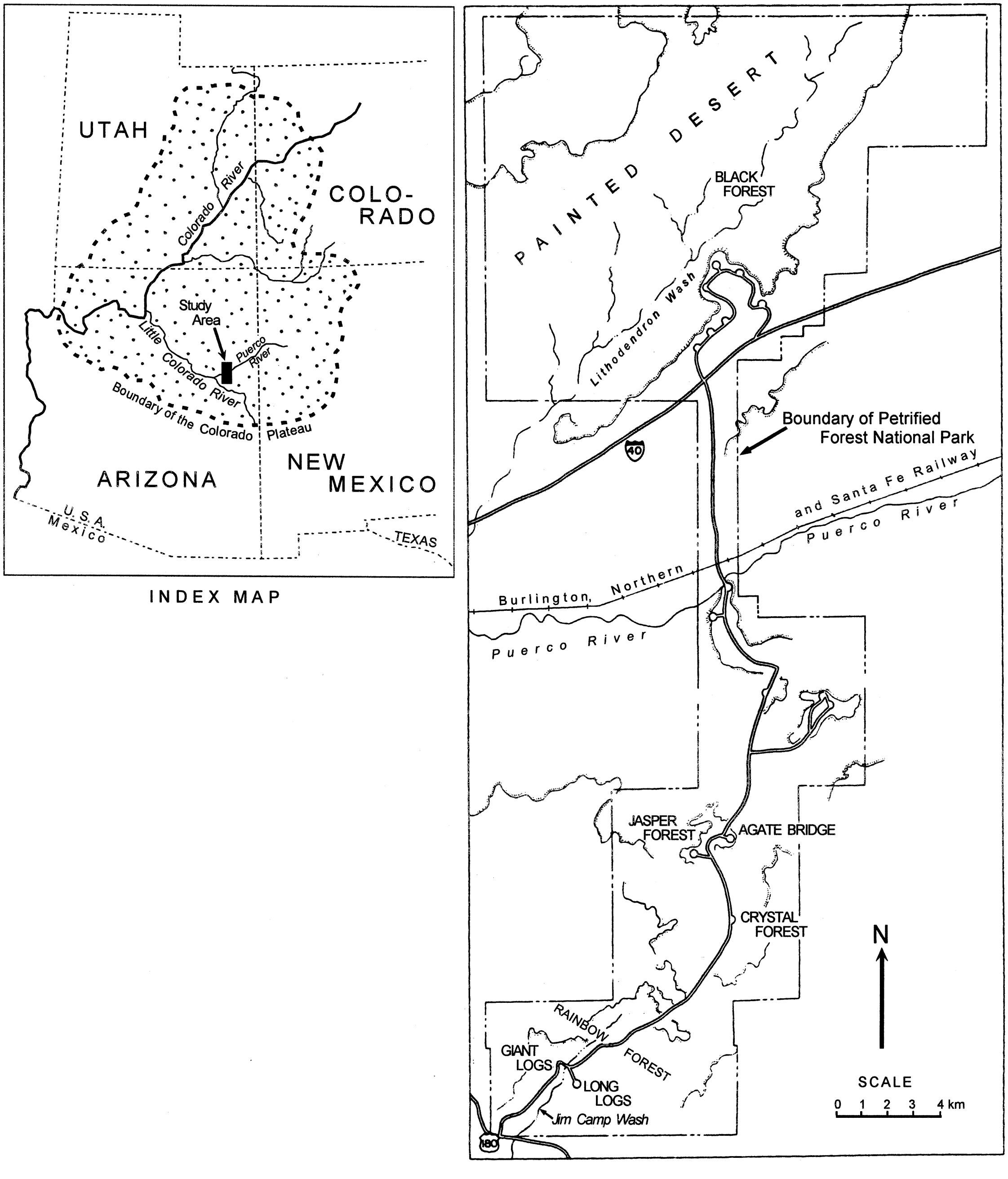

TEXT-FIG. 1. Map of Petrified Forest National Park and vicinity, east-central Arizona showing the location of the forests containing the trunks of the *Araucarioxylon arizonicum* tree and other geographical features. The smaller index map shows the location of the study area relative to the Colorado Plateau (stippled) and other features in the south-western United States (adapted from Ash 1987, fig. 1).

in some places. The formation is divided into several discontinuous lithostratigraphical units (Stewart *et al*. 1972). Those recognized in the Petrified Forest National Park and their relative thicknesses are given in Text-fig. 2. The Chinle Formation is widely exposed in the park, dipping to the north at a low angle. As a result the youngest part of the Chinle Formation is present only in the northern part and the oldest is to the south.

Most of the petrified trunks are preserved in low-sinuosity channel facies according to Demko (1995). He found that those in the middle of a channel deposit are orientated obliquely to the palaeocurrents and appear to have been grounded on the downstream faces of mid-channel bars, later buried by bedform migration. The trunks on the margin of a channel are aligned sub-parallel to palaeocurrents and probably fell in after cut-bank erosion. Living as they appear to have done, as very deeply rooted trees near a river system in the Late Triassic palaeotropics (15–18° N) the trunks do not exhibit regular growth rings (Ash and Creber 1992) since their substantial root systems conferred immunity to fluctuations in precipitation. This important fact has been noted by Nepstad *et al.* (1994) in the Amazon rain forest at the present day.

DISTRIBUTION OF THE TRUNKS

The trunks in the park are very discontinuously distributed both geographically and stratigraphically. Most lie parallel to the bedding of the Chinle Formation in the large discrete concentrations termed forests which have been given distinctive names based on a special or noteworthy character of the trunks found in each. The forests will be considered in order from north to south, also their order from youngest to oldest (Text-fig. 2). The northernmost and youngest is the Black Forest in the Painted Desert section of the park near Lithodendron Wash (Text-fig. 1) where the trunks occur in the Black Forest Bed of the Petrified Forest Member of the Chinle Formation (Ash 1992) (Text-fig. 2). Here, as the name of the forest implies, most of the wood is black. A sample of these *A. arizonicum* trunks was examined and measured.

In Jasper Forest which is *c.* 33 km south of the Black Forest the wood is typically reddish in colour and consists mostly of short lengths of the trunks of the *A. arizonicum* tree. The majority were embedded in the Sonsela Sandstone Bed but have been redeposited by Recent erosion into a basin about 80 m below that unit. During redeposition the trunks became fragmented and their parts separated and scattered. Only a few trunks remain exposed in the Sonsela Sandstone Bed at the top of the cliffs surrounding the basin. Because of their short lengths, none of the trunks in Jasper Forest was examined during this investigation.

Crystal Forest, so named because its wood contains crystal-filled cavities, lies 4 km south of Jasper Forest. Hundreds of long trunks of *A. arizonicum* trees are exposed. Apparently, they originate from both the Sonsela Sandstone Bed and the subadjacent strata of the Chinle Formation. A large number of trunks in this forest was examined because so many are complete and well exposed.

Rainbow Forest, the southernmost of the forests is about 10 km south of Crystal Forest, near the south entrance to the park. The wood in this forest is usually very colourful and is attributed to the *A. arizonicum* tree. The trunks occur in what was termed by Cooley (1957, 1959) the Rainbow Forest Bed, which is either just below the Sonsela Sandstone Bed or equivalent to it. Rainbow Forest is subdivided by Jim Camp Wash into two sections (Text-fig. 1). To the east of the wash is the Long Logs Section which contains some of the longest trunks in the park. In the Giant Logs Section west of the wash the diameters of the trunks are especially large. Many of the trunks studied were in Rainbow Forest, particularly in the Long Logs Section.

The trunks are broadly divided into two groups (Demko 1995). In the first group, the trunks are more randomly arranged having been transported from their original growth sites and then deposited on large barforms in the channel. In contrast, the trunks in the second group are deposited much nearer to their growth sites after rotation on their root-plates in a downstream direction. In this group, there was interference between trunks so that they came to rest in log jams (Pl. 1, fig. 4).

The number of exposed trunks varies greatly from place to place. For example, the four 1000 m^2 quadrats in the Long Logs and Giant Logs areas (Text-fig. 1) were found to contain 20, six, five and five trunks respectively. Some of this variation is certainly related to the local environment of deposition as recognized by Demko (1995) but an unknown amount may be related to the removal of trunks which occurred in the park before the practice was restricted in 1906.

MATERIAL AND METHODS

In 1997, we began a systematic study of the trunks attributed to *A. arizonicum* in the Petrified Forest and examined several hundred. The entire trunk heights in life could not be measured directly because, with one known exception (Pl. 3, figs 3–5), the topmost parts of the trunks are not preserved. Eleven of the longer trunks were studied in detail and their probable heights in life were calculated. Measurements of the basal diameters of the trunks were made at an assumed ground level at the position of the highest of the root bifurcations. Also, a limited number of quadrat studies were undertaken to compare the distribution of trunks in different parts of the park.

Height of trees

Data taken from the 11 trunks selected for detailed study are presented in Table 1. The trunks were all non-bifurcated with the uppermost portions missing but with their root systems still attached. The heights of these trees when living were estimated by using the allometric method of Niklas (1994*a*), which is based on very large numbers of measurements of the heights and basal diameters of extant trees.

The data from the 11 selected trunks in the park have been calculated and appear in Table 1, with the estimated heights of the trees adjusted as described above. In order to avoid reconstructing a tree to a height that would not be viable, it is possible to use the formula for the critical buckling height (H_{crit}) of a tree (Niklas 1994*b*):

$$H_{crit} = C\left(\frac{E}{\rho}\right)^{1/3} D^{2/3}$$

where C is a constant, 0 ·792; E is Young's modulus (10^6 kg m^{-2}); ρ is the wood density (kg m^{-3}); D is the basal diameter, (m). The figures used for E and ρ are the means for 18 extant conifers cited by Niklas.

The critical buckling height is the height at which the mechanical structure of the wood would fail, leading to the collapse of the tree. Commonly, trees grow only to a height that is not less than about one-third of the critical height. The critical buckling heights of the selected trees have been calculated and appear in Table 1 together with the safety factors. The latter are calculated by dividing the critical buckling heights by the projected heights. Many of the trunks were obviously of very large trees. For example, trunk No. 7 with a basal diameter of 1· 53 m has an estimated height of *c*. 45 m. Similarly, trunk No. 24 with a basal diameter of 1· 24 m has an estimated height of more than 42 m. Twenty-two of the 35 trunks examined had basal diameters of more than 1 m.

Three trunks in the Forest are know by special names. 'Old Faithful', in the Giant Logs area of Rainbow Forest, was in life undoubtedly very large, having a basal diameter of 2·9 m and a diameter of 1·26 m, 10·2 m above the base. Although only 32 m remains now it was probably originally 59 m tall. The other two are 'natural bridges' which arose because surface water flowed under them as they lay fortuitously across the stream, leaving them suspended by their extremities. 'Agate Bridge' *c.* 3 km east of Jasper Forest, which occurs in the Sonsela Sandstone (Text-fig. 2), has a basal diameter of 1·24 m, tapering to 0·5 m, 26 m above and is 28 m long, originally being *c.* 32·5 m. 'Onyx Bridge', in the Black Forest, is

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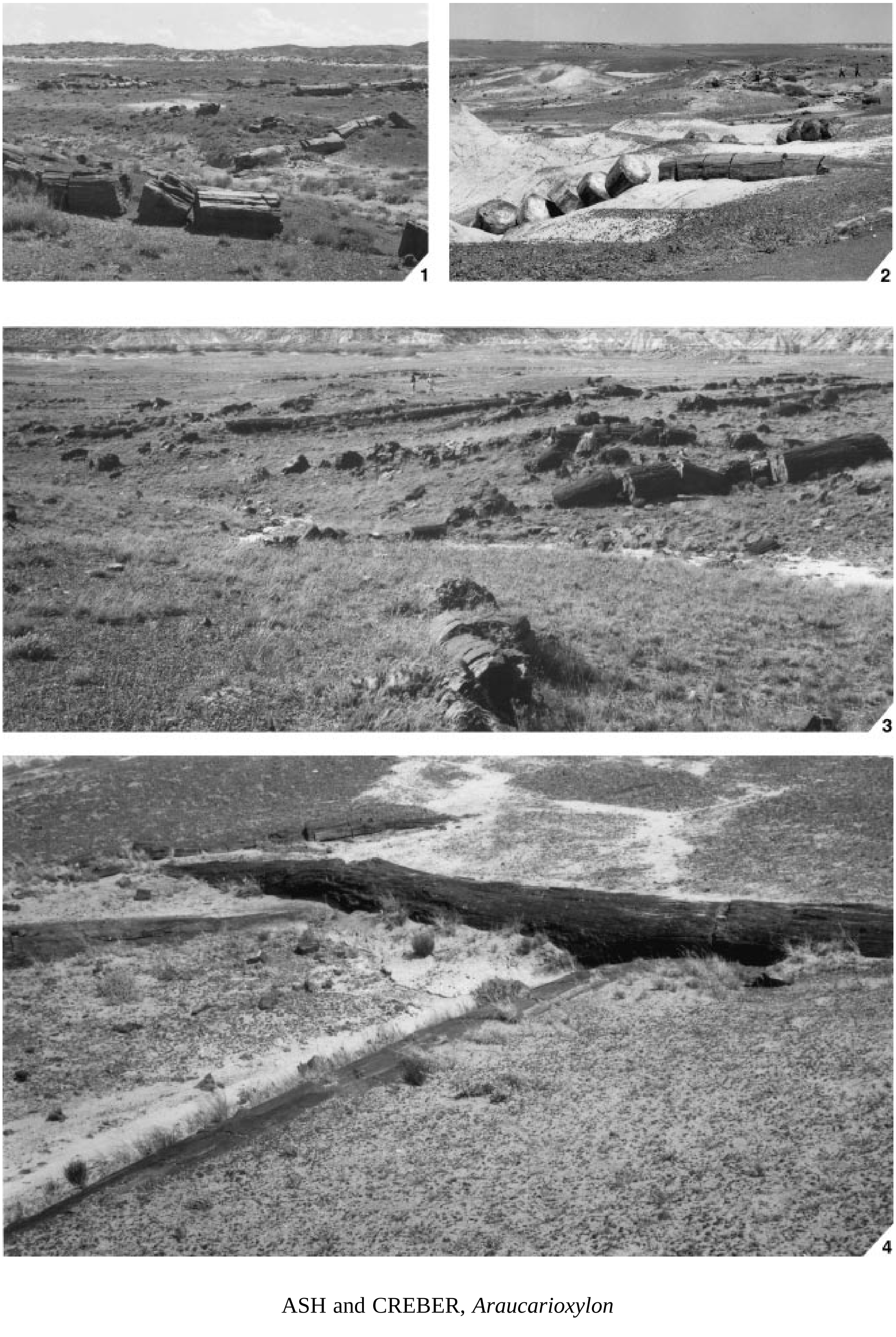
EXPLANATION OF PLATE 1

Figs 1–4. Trunks of the *Araucarioxylon arizonicum* tree. 1, trunks exposed on the surface of the Black Forest Bed; trunk in foreground is *c.* 0·9 m in diameter; Black Forest Section. 2, a trunk fragmenting transversely downslope as it is exposed by erosion of the strata directly below the Sonsela Sandstone; trunk is *c.* 0·84 m in diameter; Crystal Forest. 3, high density collection of nearly parallel trunks eroding out of the Sonsela Sandstone; most of the logs are oriented east–west; human figures in the background indicate scale; Long Logs Section of Rainbow Forest. 4, an apparent log jam exposed by erosion; note that the dark log extending from right to left is curved where it crosses the underlying logs; Long Logs Section of Rainbow Forest.

PLATE 1



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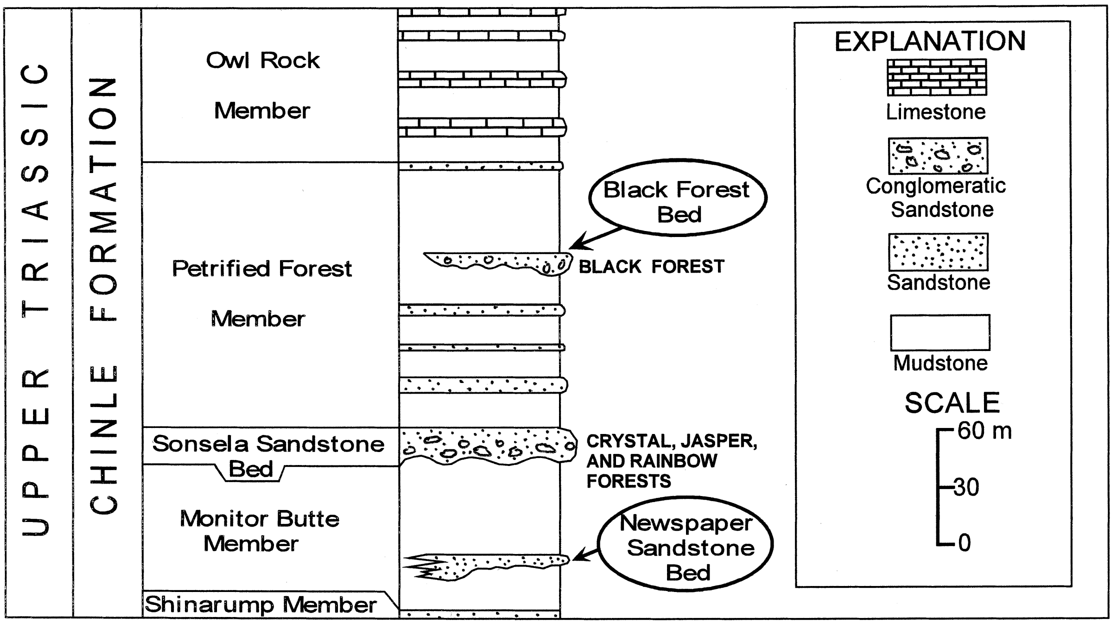


TEXT-FIG. 2. Chart showing the members of the Chinle Formation exposed in the Petrified Forest National Park and their relative thicknesses and lithology (adapted from Ash 1987, fig. 1).

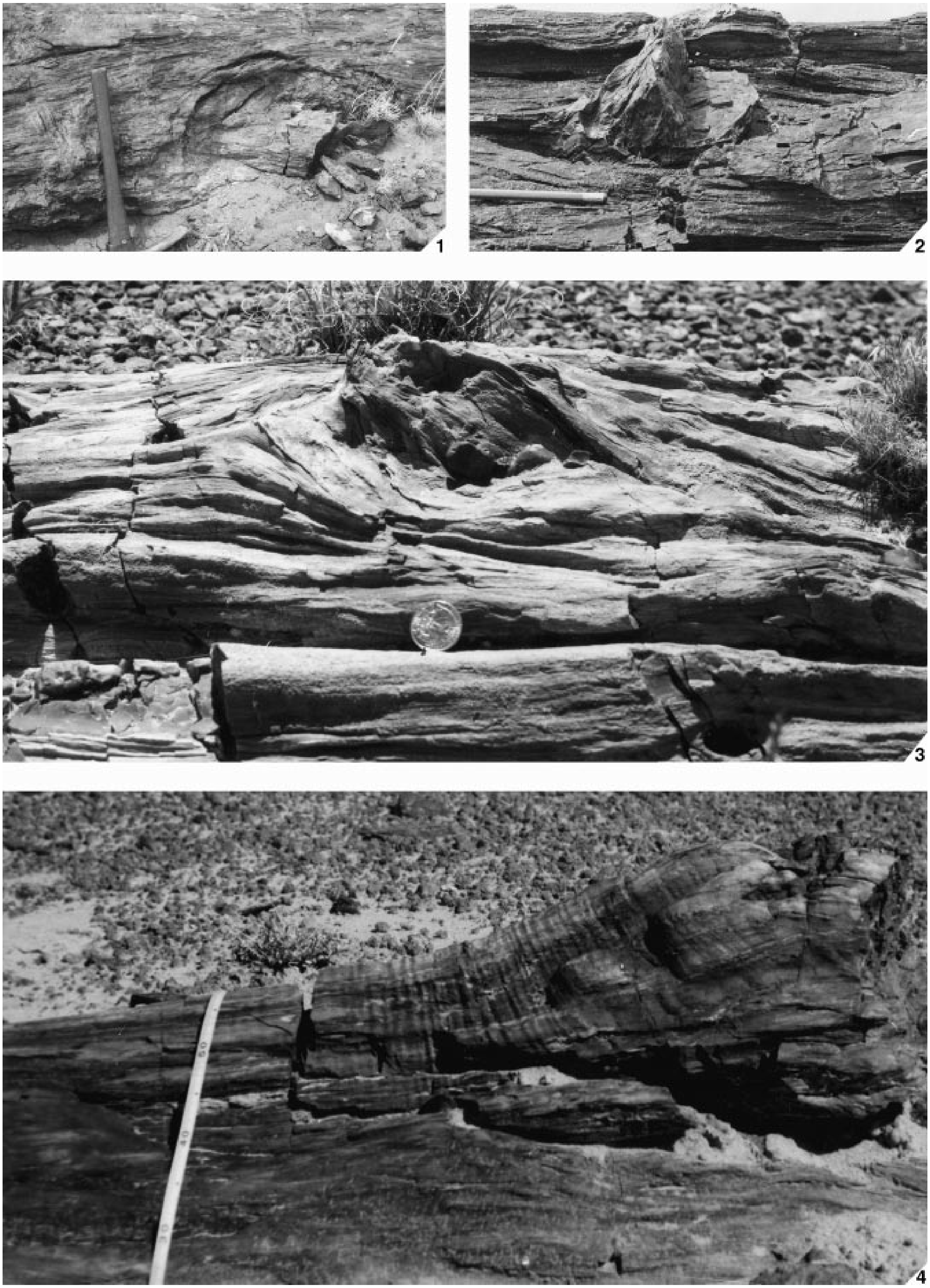
TABLE 1. Dimensions of selected petrified trunks of the *Araucarioxylon arizonicum* tree in Petrified Forest National Park, Arizona, USA. D, diameter at ground level; L, length of trunk on desert floor; Est. H, estimated height; Crit. H, critical buckling height; SF, safety factor.

Trunk No.	D (m)	L (m)	Est. H (m)	Crit. H (m)	SF
5	1·0	36·6	38·9	97·5	2·5
6	1·38	20·0	43·8	121·0	2·8
7	1·53	40·8	45·3	128·8	2·8
8	1·71	15·7	46·9	139·0	3·0
18	0·94	25·5	38·0	93·7	2·5
19	1·07	11·5	39·9	102·0	2·6
24	1·24	26·0	42·2	112·5	2·7
25	1·13	14·9	40·8	109·8	2·7
30	0·82	1·8	35·9	73·6	2·1
31	1·15	2·3	41·0	90·6	2·2
32	1·45	12·05	44·5	113·2	2·5

EXPLANATION OF PLATE 2

Figs 1–4. Branch scars with short remnants of lateral branches on the trunks of the *Araucarioxylon arizonicum* tree. 1, the pick handle is 0·43 m long; Long Logs Section of Rainbow Forest. 2, pencil is *c.* 6 mm in diameter; Long Logs Section of Rainbow Forest. 3, the coin is *c.* 22 mm in diameter; Crystal Forest. 4, base of a lateral branch on a trunk showing transverse ridges of compression wood; the tape divisions are in mm; Crystal Forest.

PLATE 2



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0·68 m in diameter at its widest and 0·44 m at its narrowest at a distance of 16·1 m. Although its roots are not seen, the data indicate that it was about 22·5 m tall in life.

Branches

The trunks exhibit large numbers of clearly exposed branch scars (Pls 2–3) occurring almost to ground level. In general, little or nothing remains of the branches but one was observed in the Black Forest which was exceptional. It had a diameter of 0·2 m where it diverged from the trunk and was 1·5 m long at which point the broken end was 8 mm in diameter. Also a number of trunks retain short projecting bases of branches (Pl. 2, figs 1–3; Pl. 3, fig. 2) and prominent compression ridges are present on the surface of the basal parts of some of them (Pl. 2, fig. 4).

Measurements of the positions, lengths and breadths of many branch scars were taken from trunks. It was noticeable that the branches diverged upwardly at angles between 30 and 40 deg. (Pl. 2, figs 1–3) to the surface of the trunks. The bases of the branches ranged from *c*. 20 mm in diameter (Pl. 3, figs 3–5) to as much as 150 mm. The branches typically occur slightly above the centre of a longitudinally oriented, lens-shaped depression which ranges from 50–400 mm long and 30–200 mm wide depending upon the size of the branch. In some cases the wood on the trunk surrounding the branch flares outward as much as 200 mm (Pl. 3, fig. 2).

Ash (1987) noted that the branch scars are not arranged in whorls and each is often isolated from others by several hundreds of millimeters, measured in either a vertical or horizontal direction (Pl. 3, fig. 2). However, in a few instances two or three branch scars may be much more closely arranged and some are almost in contact (Pl. 3, fig. 1). Another exception is a trunk *c*. 8·05 m long and 0·56 m in diameter in Crystal Forest (Pl. 3, figs 3–5) where all of the scars are closely arranged – usually only several mm distant from each other – in contrast with the situation in all other trunks studied. Also, they are relatively small (*c*. 10–20 mm in diameter) in comparison with those on most other trunks. The slight taper of this trunk indicates that it was the upper part of a tree, whereas all the others examined came from the lower part of the *A. arizonicum* tree.

Whilst allowance must be made for the possible loss of some of the outer wood, the lowest branch scars are so clearly defined that they appear to be of branches that still carried viable foliage and were not in the process of being overgrown by wood after self-pruning (Pls 2–3). The cut-bank activities of the river terminating the lives of the trees before they had reached the end of their potential life spans may have led to the situation whereby they still had viable lower branches when they were toppled. In some cases the trunks apparently have lost none of their outermost wood since the tracks of two different species of bark beetles are to be seen on some trunks (Pl. 3, fig. 2). Furthermore, the projecting bases of branches which are found on a number of trunks (e.g. Pl. 2, figs 1–3; Pl. 3, fig. 2) could not have survived the abrasion necessary for removal of the outer wood. Finally, the wood surface of the only specimen found with bark is comparable to those of all other trunks observed.

Bark

The bark specimen is on a small branch or trunk *c*. 0·7 m long and 0·15–0·17 m in diameter (Pl. 4, fig. 5). It is *c*. 10 mm thick and shows structural characteristics of scale bark. The tissue consists of an outer layer of

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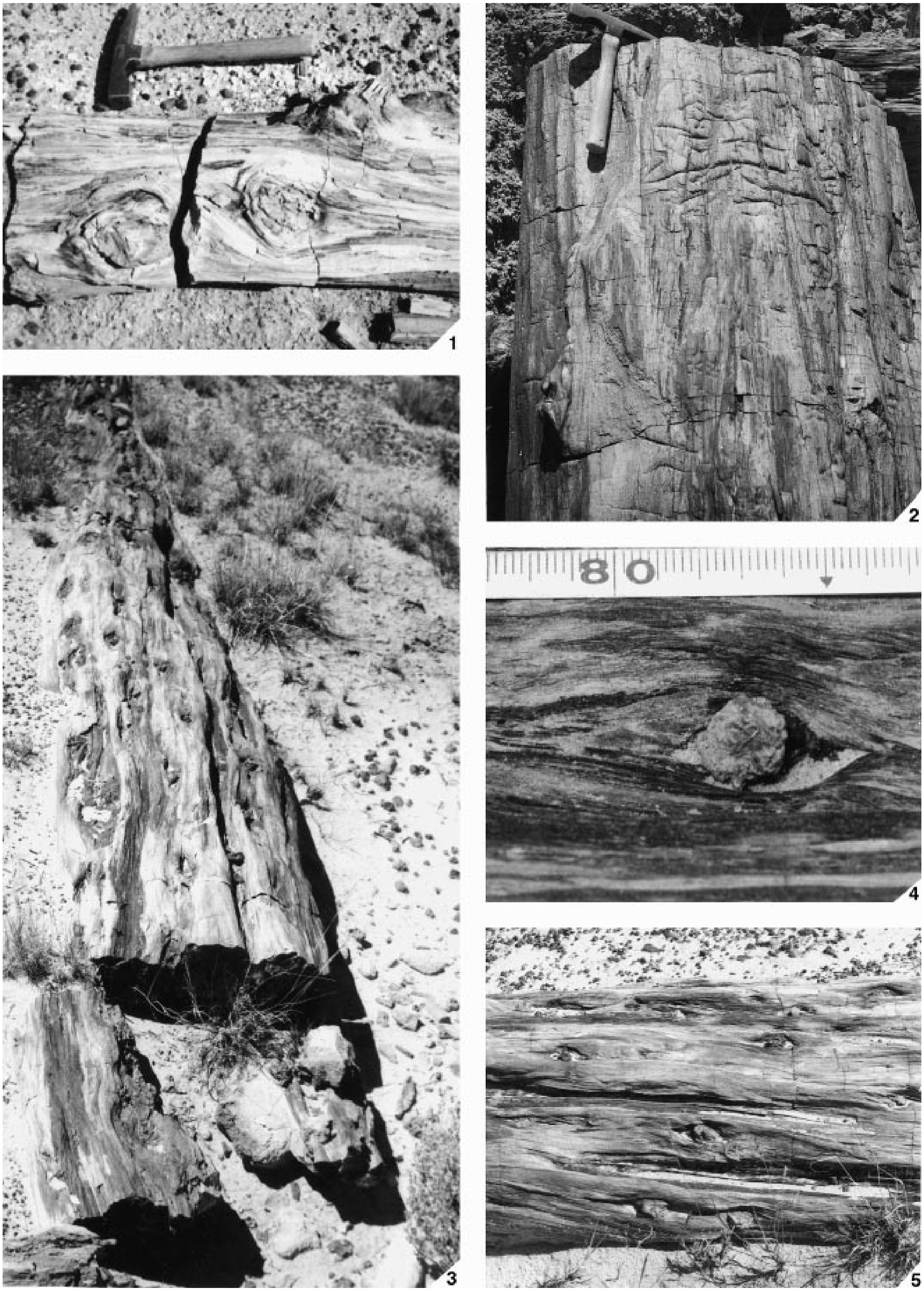
EXPLANATION OF PLATE 3

Figs 1–5. Branch scars and beetle tracks on the trunks of the *Araucarioxylon arizonicum* tree. 1, three unusually closely arranged branch scars on a portion of a fractured trunk; Giant Logs Section of Rainbow Forest; hammer handle is 0·7 m long. 2, tracks made by *Paleoscolytus divergus* Walker; Black Forest; hammer handle is 0·7 m long; ×0·25. 3, upper portion of a trunk with numerous small and a few larger branch scars; Crystal Forest. 4, detail of a branch scar with remains of a lateral branch from the trunk in fig. 3; Crystal Forest. 5, portion of the trunk shown in fig. 3 showing numerous, closely arranged, branch scars each containing the remains of small lateral branches; Crystal Forest.

PLATE 3



ASH and CREBER, *Araucarioxylon*, *Paleoscolytus* tracks rhytidome *c*. 6–8 mm thick and a thin (2–4 mm thick) inner layer of structureless mineral matter representing the vascular cambium and phloem. This layer is attached to the outer surface of a woody cylinder that has the wood anatomy of the *A. arizonicum* tree. The rhytidome consists of several discontinuous overlapping shell-shaped layers of periderm. There is no evidence of lenticels and resin canals in any of the tissue. The wood bearing the bark came from the Black Forest Bed (Text-fig. 2). The fact that the bark of these trees was somewhat thin may explain why this is the only fossilized bark specimen found in the Chinle Formation. Furthermore, since these trees would not have to be protected against frost, there was no environmental pressure from this phenomenon to develop a thick bark.

Roots

As previously reported (Ash 1987), many of the trunks have retained the upper part of the root system which flares out by as much as 0·5 m at the base of each log (Pl. 4, figs 3–4). The root system is very large, usually consisting of a central tap root and four to six peripheral laterals (Pl. 4, fig. 3). In some cases the laterals may be of considerable size. Three of those on tree No. 32 (Table 1) were each 270 mm, 350 mm and 250 mm respectively in diameter measured at *c*. 0·5 m from the base of the trunk. The tap roots usually are similarly massive and attain a diameter of as much as 0·330 m at the base and have a length of more than 5 m (Pl. 4, figs 1–3, 6). Such massive roots are an indication that the trees grew in relatively soft, alluvial soil near to a river system. A tree 30 m tall obviously exerts considerable leverage on its roots and the latter would need to have penetrated to a considerable depth to hold the tree upright. The fact that the roots are still attached to the trunks is evidence of their felling by the cut-bank action of the river.

This type of root system is at variance with that seen at the present day in members of the Pinaceae such as *Pinus* and *Abies* and the Araucariaceae such as *Araucaria*. In such trees the roots are small, narrow and numerous so that a fallen pine is almost always seen to have pulled up a circular, flat plate of soil. However, it must not be assumed that tap roots are unknown in conifers. Gasson and Cutler (1990), in their survey of trees uprooted in the gales of 1987 in south-east England, found that two out of eight specimens of *Chamaecyparis*, one out of 27 of *Larix* and two out of 43 of *Pinus* had tap roots. The two specimens of *Araucaria* that they observed also lacked tap roots.

Foliage and reproductive structures

Although some coniferous foliage and reproductive structures have been found in the Chinle Formation in the park and elsewhere (Ash 1980) none is directly associated with the trunks of the *A. arizonicum* tree. Also, the sediments adjacent to the trunks typically do not contain other plant megafossils. This situation is thought to indicate that the valley floor was swept clear of small fragments of plant material by the constant bedform migration of a meandering river.

CONCLUSIONS

On the basis of data obtained from a large number of trunks examined throughout the park we have concluded that the *A. arizonicum* tree was monopodial and, when mature, had a diameter of *c*. 1–3 m at breast height and stood as much as 59 m tall when alive (Text-fig. 3). The trunk tapered evenly from a very

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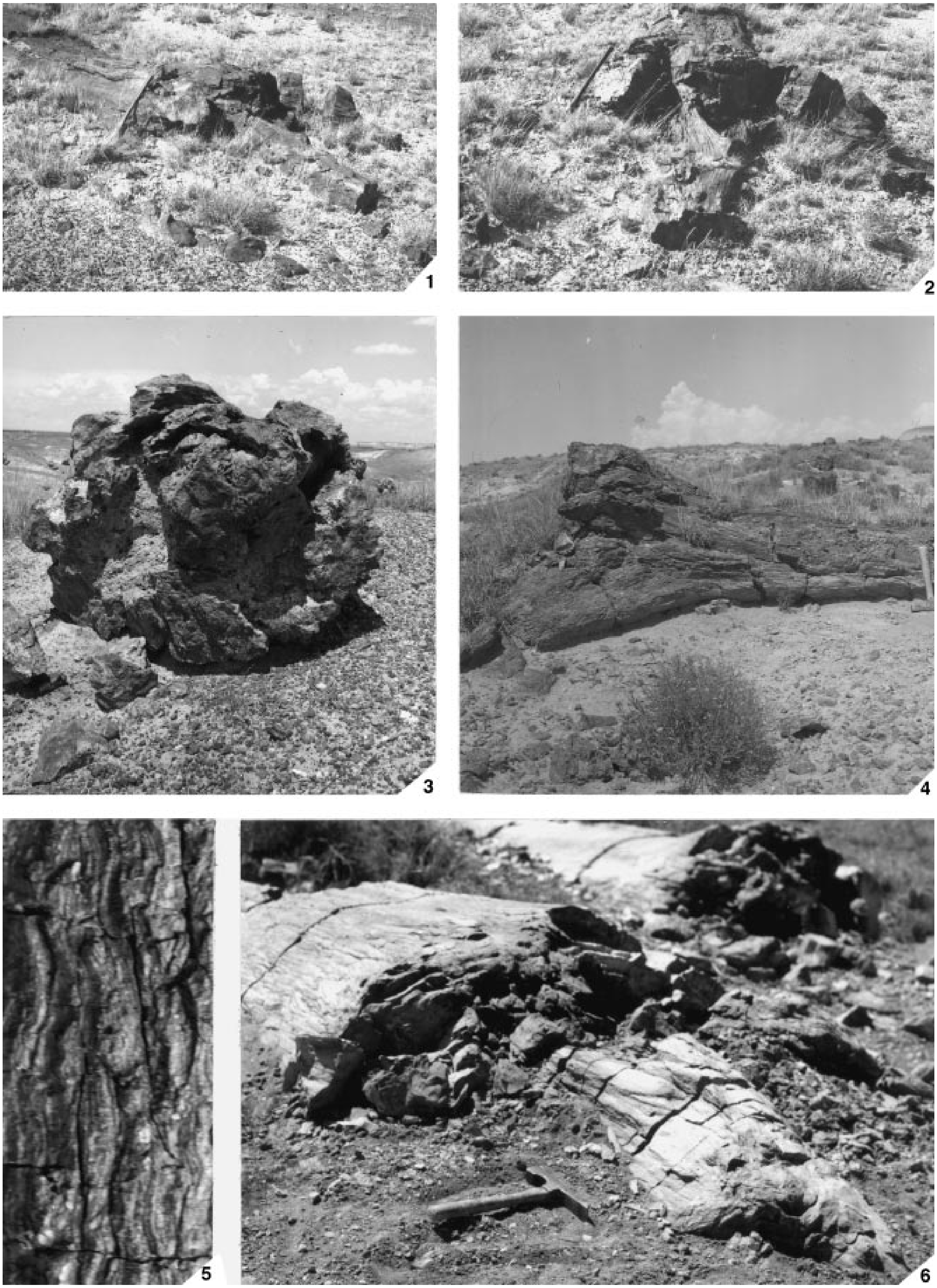
EXPLANATION OF PLATE 4

Figs 1–6. Root system and bark of the *Araucarioxylon arizonicum* tree. 1–2, side and basal views of a root system with two laterals and a prominent tap root; hammer handle is 0·8 m long; Long Logs Section of Rainbow Forest. 3, view of the base of a trunk showing large tap root and peripheral laterals; the light-coloured conglomeratic sand between the roots may represent the original soil; Crystal Forest. 4, lateral view of trunk base with transition to root system; rucksack for scale; Black Forest. 5, Bark on branch or small trunk of the *Araucarioxylon arizonicum* tree; Black Forest. ×0·5. 6, Root system with large tap root; Long Logs section of the park; hammer handle is 0·7 m long.



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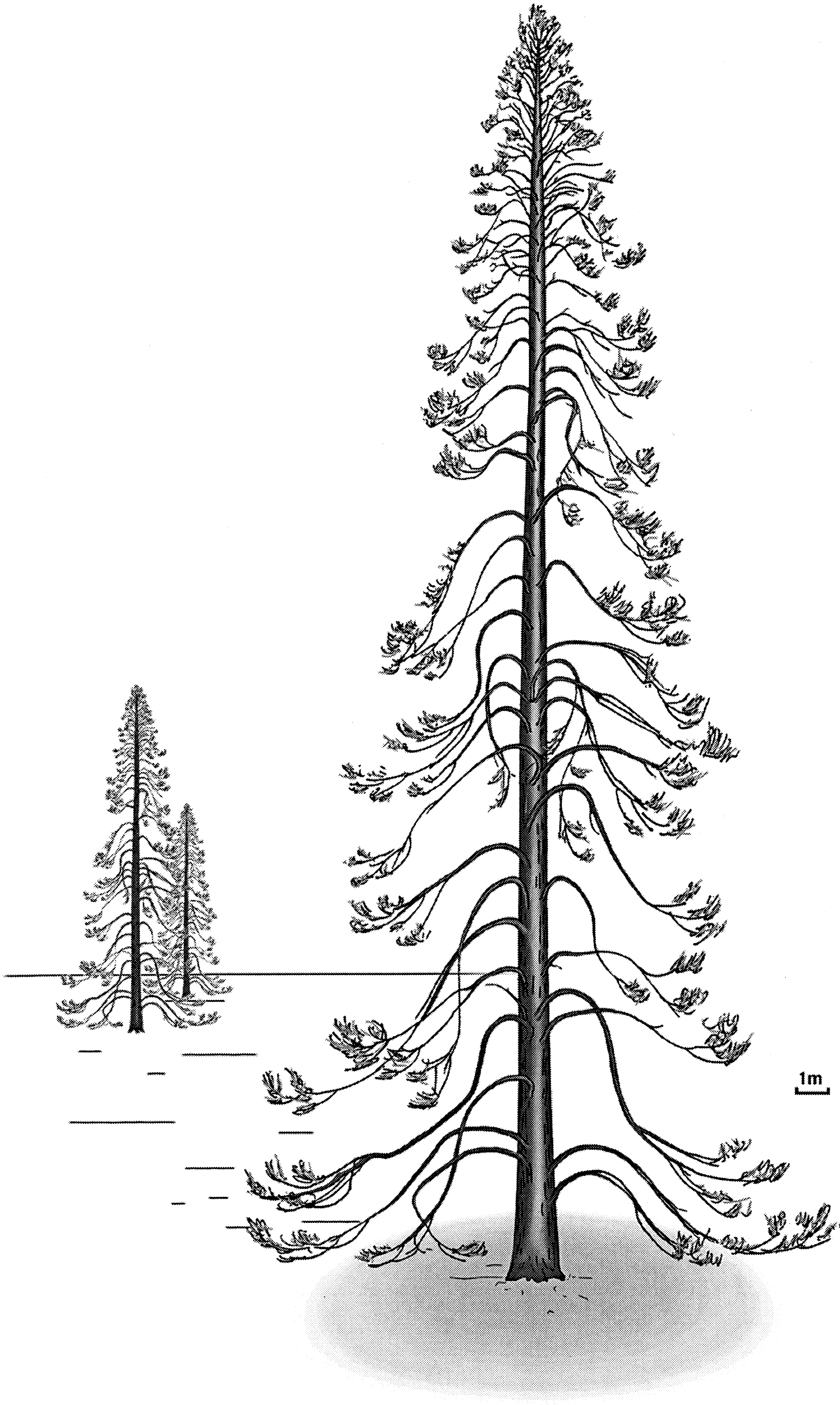

TEXT-FIG. 3. A reconstruction of the *Araucarioxylon arizonicum* tree.

slightly expanded base to the top and was held upright by a ring of broad lateral roots growing into the ground at steep angles and a long, stout, downward-directed tap root. The branches had no systematic arrangement on the trunk and diverged from it at steep upward angles. Because the tree was growing in the tropics it is likely that the branches then subsequently swept downward and outward so as to present an appreciable area of foliage to the solar radiation which, for most of each day, came down directly from above. The apices of such branches, as for example in *Sequoiadendron giganteum* (Lindley) Bucholz, are negatively geotropic and turn slightly upwards. For the most part the branches, even the lowest ones on the trunk, might well have carried viable foliage until the tree died. Since we have no direct evidence of the foliage it is only generalized in the reconstruction. Based on one specimen, the bark was thin and the scale type and had no unusual characteristics.

The resulting reconstruction we present is at considerable variance with those presented elsewhere. Apparently, because of the mistaken belief that wood assigned to *Araucarioxylon* was necessarily derived from a close ancestor of the living *Araucaria* tree of the southern hemisphere authors used that tree as a model instead of looking at the actual trunks when they reconstructed the *A. arizonicum* tree. For example, the reconstruction of a Triassic scene published by McKee *et al.* (1959) shows *A. arizonicum* trees with dome-like crowns composed of whorls of branches similar to those of *Araucaria bidwillii* Hook, with only a few lateral branches in whorls on the lower portions of the trunks. Later, Gottesfeld (1972) published a reconstruction of the tree in which the trunks are shown devoid of lateral branches virtually from the somewhat domed crown consisting of branch whorls to ground level as in species of *Araucaria*. Furthermore, he stated that the branches were absent in the lower parts of the trunk because of self-pruning. We have produced evidence that refutes this argument.

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