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INDUSTRIAL X - RAY COMPUTED TOMOGRAPHY APPLIED TO PALEOBOTANICAL RESEARCH

MILENA PIKA-BIOLZI[1], PETER A. HOCHULI[2] & ALEXANDER FLISCH[3]

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Riassunto. La tomografia computerizzata (CT) è una tecnica di ricerca relativamente nuova, utilizzata soprattutto in Paleontologia degli invertebrati. La CT consente di visualizzare le strutture interne dei fossili e delle rocce senza che gli oggetti vengano distrutti, allo stesso modo in cui la tomografia applicata in medicina, permette di analizzare l'interno del corpo umano. Gli scanners industriali ad alta risoluzione forniscono sezioni trasversali di fossili con una risoluzione di 20 microns o meno. In questo lavoro viene presentata l'applicazione della CT a due esemplari di una collezione di Paleobotanica: il tronco pietrificato di una *Cycadeoidea* dal Giurassico dell'Inghilterra e il cono silicizzato *Araucaria mirabilis* del Giurassico della Foresta Pietrificata del Cerro Cuadraro in Patagonia (Argentina). Nelle tre sezioni longitudinali e nelle quattro sezioni trasversali del tronco di *Cycadeoidea* si possono osservare numerose strutture interne, tra cui il midollo, il corpo legnoso, la corteccia, i fasci conduttori, i coni dei fiori e le basi delle foglie. Nelle sezioni mediane, longitudinale e trasversale, del cono perfettamente conservato di *Araucaria mirabilis*, sono chiaramente visibili il midollo del cono, i fasci conduttori, i semi, le scaglie ovulifere e le basi delle foglie. Per valutare la risoluzione della CT, un secondo esemplare di *A. mirabilis*, meno ben conservato del primo, è stato utilizzato per preparare una sezione sottile.

Abstract. X-ray computed tomography (CT) is a relatively new technology which has been used as a powerful research tool mainly by vertebrate paleontologists. CT allows scientists to visualise internal features of fossils and rocks non-destructively, just as medical scanners do for the human body. High-resolution industrial scanners provide cross-sections of fossils at a resolution of 20 microns or less. We present the application of CT to two paleobotanical specimens: a petrified trunk of a *Cycadeoidea* from the Late Jurassic of England and a silicified cone *Araucaria mirabilis* from the Jurassic Cerro Cuadraro Petrified Forest in Patagonia, Argentina. In the three longitudinal and four cross-sections of the *Cycadeoidea* trunk, a multitude of internal structures could be observed, including pith, xylem, cortex, vascular bundles, floral cones and leaf bases. In central longitudinal and median transverse sections of the perfectly preserved cone *Araucaria mirabilis* pith, xylem, vascular bundles, seeds and ovuliferous scales are clearly visible. In order to test the resolution of the CT a second, less complete but similarly well preserved specimen of *A. mirabilis* has been cut and sliced for a thin section.

Introduction.

The discovery of X-rays by Wilhelm Conrad Röntgen in1895 (cf. Leicht, 1994) made the internal examination possible of a variety of objects, including anatomical structures. X-ray technology for medical applications spread very quickly, culminating in the development of computed tomography (CT) by Houndsfield (1972). CT can provide virtual cross - sections of various objects. Tomograms include accurate information on the size and position of internal features of an object, such as organs or tumours in medical applications. Applications of CT for non-destructive testing of industrial products or for inspection and data generation from geologic and paleontological objects have more recently emerged (Conroy and Vannier, 1984, 1987; Zonnefeld, 1989; Rowe et al., 1995; Zollikofer et al., 1995; Spoor, 1997; Steiger et al., 1997). In contrast to medical systems, however, industrial CTs have higher spatial and contrast resolution. These devices use higher energy radiation, which allows the penetration of objects with high X-ray densities and absorption.

The need to observe and study the internal structure of fossils is a challenge for paleontologists. For some fossil groups (e.g., corals, rudists, and brachiopods) this information is crucial for specific classifications. Until recently, the most frequently used technique in this regard has been the preparation of thin sections or polished slabs of the fossil specimens and study under a microscope (Boullier, 1976; Sulser, 1995). This method provides very good results, but it is destructive, as the fossil must be cut in several pieces. It is not, therefore, applicable to valuable specimens. Peyer (1931) was among the first paleontologists who utilised X-rays to study fossils of reptiles. Later, Conroy and Vannier used

[1] Department of Earth Sciences, ETH Zurich, Switzerland and Department of Earth Sciences, University of Parma, Italy (pika-biolzi@erdw.ethz.ch and biolzi@ipruniv.cce.unipr.it)

[2] Department of Earth Sciences, ETH Zurich, Switzerland (hochuli@erdw.ethz.ch)

[3] Swiss Federal Laboratory for Materials Testing and Reseach, Section Nondestructive Testing (EMPA), Dübendorf, Switzerland (alexander.flisch@empa.ch)

CT to investigate the skull of a Middle Miocene ungulate *Stenopsochorus* from Wyoming (1984) and to reconstruct the skull of an extinct African monkey (1987). More recently Steiger et al. (1997) reported the application of Nuclear Magnetic Resonance tomography in palaeontology. However, in many cases the radiation energy of readily available medical systems is insufficient. Industrial tomography provides a solution in such cases. Unfortunately industrial systems are not widely distributed and very few institutes provide this service to third parties.

Method.

Detailed information on CT has been published by Moore (1990) and Wells et al. (1994). Our article intends to clarify several basic points in order to show which palaeontological, and more specifically palaeobotanical applications can reasonably be implemented. In principle we can differentiate between limitations inherent to particular methods and those due to the technical specifications of the devices.

Industrial tomographic scanners are available in a wide range of dimensions. For example, so-called microtomographs can only be used to investigate small objects (diameter 20 to 30 mm), but have a spatial resolution of up to 20 μm. Some devices are designed to accommodate large objects with dimensions up to several meters. Micro CTs are used more widely than large systems because of the considerably lower financial investment. For most analyses of macropalaeontological objects, neither the large systems nor the micro CTs are needed.

The image quality and, therefore, the value of results derived from a tomogram depends mainly on the spatial and contrast resolution as well as on the signal-to-noise ratio. The achievable spatial resolution is a function of the geometric specifications of the scanning system, the size of the object being examined, the detector and the X-ray source used. Microfocus X-ray tubes are applied to achieve the highest possible spatial resolution. However, this type of X-ray source is characterised by low intensity and can only penetrate objects with thin walls or with low X-ray density. In order to achieve penetration of objects with strong absorption characteristics, i.e. thick-walled components with high X-ray density, the radiation energy from standard X-ray tubes is insufficient. In such cases linear accelerators are needed.

The contrast resolution depends on the energy of the radiation source, the attenuating characteristics of the material and the detector technology. By using correction algorithms and adequate filters, the contrast can be subsequently improved. Low radiation energy ensures better contrast than high energy. However, the advantages of soft X-ray energy are rarely applicable to palaeontological objects, as these objects cannot be penetrated by low energy radiation. Whether the structures of fossils can be imaged with sufficient contrast depends on the minerals that have replaced biological materials or have been deposited within cavities during fossilisation processes. These features are often difficult to estimate before an investigation and require preliminary tests. The most important limitation is the low X-ray contrast between the object and the sediment fill or the adjacent sediments consisting of material with nearly the same X-ray density.

Spatial and contrast resolutions are both dependent on the signal-to-noise ratio. The ratio improves with higher intensity at the detector and increasing radiation time. The measured radiation intensity depends on the source and the absorption by the object. For palaeontological objects the economical considerations are not crucial, and therefore, longer measurement times are acceptable.

The applications presented in this paper were performed at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Dübendorf, Switzerland using an industrial computer tomograph manufactured by Scientific Measurement Systems (SMS) Austin, Texas. This system is a medium-size device which is particularly suitable for investigating palaeontological objects. It combines the benefits of higher spatial and contrast resolution with the higher radiation energy necessary for fossils. The 450 kV X-ray tube used emits energy high enough to penetrate through up to 200 mm of sedimentary rock. The tube is highly stable and has an optically effective focal plane of 1-2 mm. As a general rule the achievable spatial resolution is in the range of 0.5 to 1 per mill of the object diameter. In order to reduce to a minimum the scattered radiation within the object and achieve a higher signal-to-noise ratio, the X-ray beam is focused by approximately 2 mm high collimators.

Material and results.

Computed tomography has been applied to different fossils stored in the collection of the Department of Earth Sciences of the ETH Zurich. The palaeobotanical specimens presented here are a petrified trunk of a *Cycadeoidea* from the Late Jurassic of England (Fig. 1) and the silicified cone of a Jurassic *Araucaria mirabilis* (Spegazzini) Windhausen, from the Cerro Cuadraro Petrified Forest in Patagonia, Argentina (Fig. 5A).

The apparently well preserved specimens were analysed to obtain detailed information on the type of preservation as a base for conservation measures and to test the applicability of the method for palaeobotany. Moreover, the high resolution tomograms are used as teaching material.

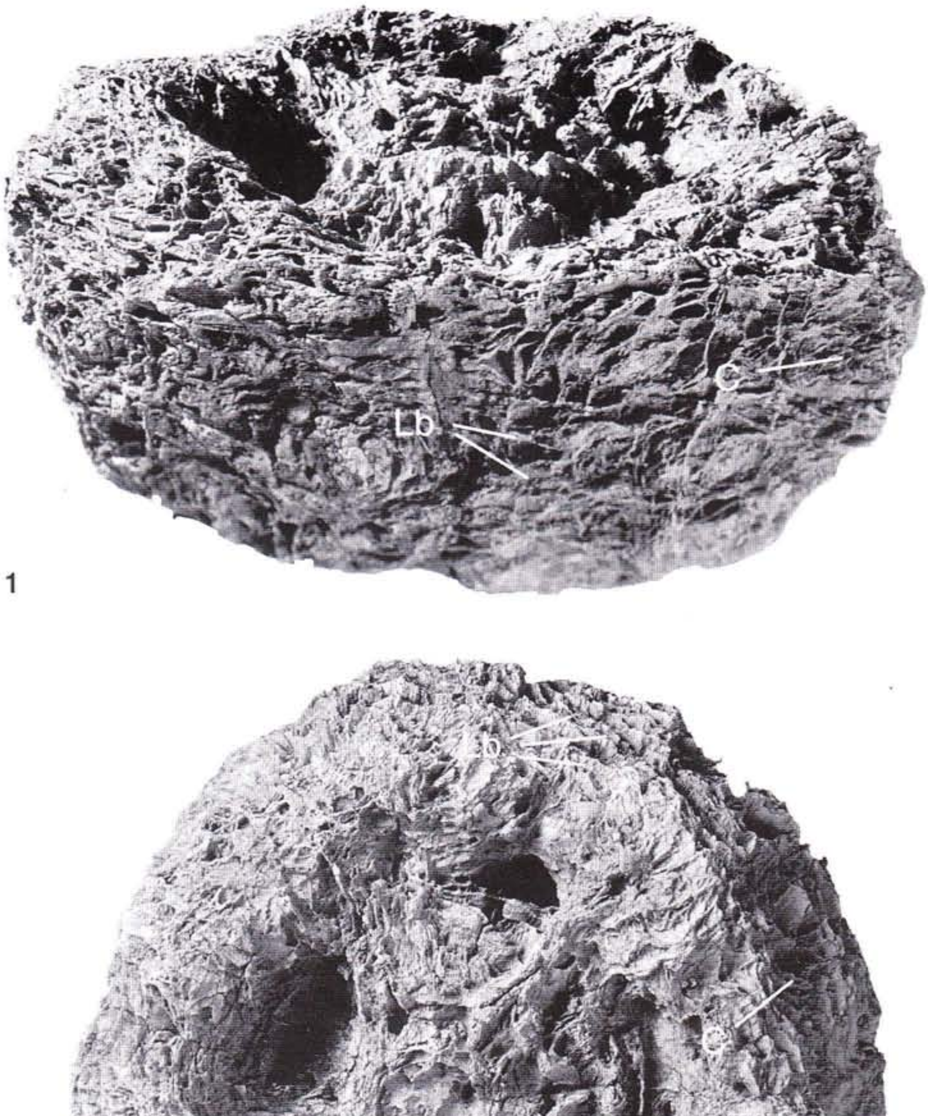


Fig. 1 - Petrified trunk of a *Cycadeoidea* from the Late Jurassic (Purbeckian) of England. C cone, Lb leaf bases.

Trunk of *Cycadeoidea* sp.

The studied petrified trunk stored in the palaeontological collection of the ETH Zurich (Fig. 1; collection number: 43/10/7) since the late 1800 was probably collected from the Purbeckian of Southern England. No other details concerning the locality or the collector are known. The organic structures have been partly replaced by silica. The trunk is of irregular discoid shape (width 250 mm, height 97 mm) with a broad convex base and a distinctly concave distal end. Thus, the widest diameter is situated in the upper third of the trunk. Several open cracks and three holes are visible in the distal portion of the trunk (Fig. 1.2). On the outer surface of the fossil several distinct structures can be differentiated. Near the base, the surface is almost smooth showing only some irregular verrucations and several well-defined circular holes (diameter ca. 5 mm). The latter can be interpreted as insertion points of roots. The main part of the surface is characterised by approximately helicoidal arranged pits, which are separated by irregularly shaped scaly protrusions (Fig. 1.1). These structures reflect the leaf bases (Lb), the pits corresponding to the softer parenchymeous parts, whereas the protrusions represent the remains of the lignified vascular bundles.

At several points this pattern is interrupted by quite well defined round to oval structures which are marked by spirally arranged traces of bracts. These areas are interpreted to correspond to cone-like caulifloral structures (C). Near the distal end of the trunk the pattern of the surface structures seems to be more irregularly arranged and is more difficult to interpret. The observed differences in preservation of these structures are obviously due to the differences in lignification of the older leaves compared to the younger ones. The observed differences in preservation between the main part of the trunk and its distal end suggest that the fresh, weakly lignified parts of the plant were severely degraded prior to mineralisation.

The overall shape of the trunk and the arrangement of the leaves and the floral organs are typical for the genus *Cycadeoidea*, a group of Mesozoic gymnosperms attributed to the cycaphytes. *Cycadeoidea*, as part of the Cycadeoideaceae family, superficially resemble the extant cycads. The genus is characterised by rel-

Fig. 2 - Reconstruction of a cycadeoid plant.

narrows near the basal, oldest part of the trunk. The pith is best preserved in its middle part (Fig. 3.2). The irregularly arranged brighter structures within this zone are probably secretory canals (Fig. 4.1). The weak contrast in the distal part could be due to weak mineralisation (Fig. 3.4).

The brightly contrasting sector surrounding the pith represents the strongly lignified woody cylinder (X: xylem, Fig. 3). The darker layer surrounding this part is less dense and shows an irregular structure (Fig. 3.1 and Fig. 4). In this zone, termed cortex (Cx), vascular bundles (Vb) are embedded in softer parenchy-meous tissue. Vascular bundles connecting the leaf bases with the woody cylinder can best be seen in Fig. 3.1.

The bright contrast of the outermost layer reflects the hard and strongly lignified armour (A) which protects the inner, more fragile parts of the trunk (Fig. 3 and Fig. 4). This layer is formed by leaf bases and partly, by remains of the floral structures (Fig. 3). The fine hair-like structures embedded between the solid leaf bases can be differentiated on neither the surface nor in the CT. The armour was certainly very hard and compact in the older portions of the trunk and less resistant to degradation in the younger parts. In the tangential longitudinal sections (Fig. 4.2-.4) spirally arranged floral structures (C: cone) are clearly visible among the leaf bases.

atively short bulbous trunks which bore big pinnate leaves and flowers (Fig. 2). The anatomy of these plants is best known from superbly preserved silicified specimens found in the Cretaceous of Wyoming and Dakota (cf. Wieland, 1906, 1916 and Delevoryas, 1960, 1963). Petrified trunks are quite frequently found in the Purbeckian of Southern England (Buckland, 1829) and in many other Mesozoic localities. The well-preserved silicified specimens reveal flower-like bisporangiate cones consisting of a spiral of numerous sterile bracts surrounding the whorl of male and female structures. The latter were organised as a receptacle with numerous small seeds. These floral structures were sitting on reduced lateral branches (peduncles) and were hardly extruding the surface of the trunk (Fig. 2).

In order to demonstrate the possibilities of the technique for the interpretation of fossil plants, four transversal cross sections and four longitudinal cross sections are shown in Fig. 3 and 4. In the CT sections, four distinct layers can be differentiated within the trunk. The innermost, relatively dark layer represents the parenchymeous cell structures of the pith (P: pith, Fig. 3.2). In central longitudinal section (Fig. 4.1) the pith can be visualised as a broad inverted cone which

Seed cone of *Araucaria mirabilis*.

The beautifully preserved seed cones of *Araucaria mirabilis* (Fig. 5) from the Cerro Cuadrado Petrified Forest from Patagonia from the palaeontological collection of the ETH Zurich (collection number: 34/9/12) are perfectly suited to test the possibilities and the limits of the CT method. The studied cones are completely silicified consisting of alpha-quarz silica (Stockey, 1975).

The cone used for CT (Fig. 5.1) has a slightly compressed ovoid shape (width 52 mm, length 58 mm). The insertion area of the peduncle (Pe) of the cone is

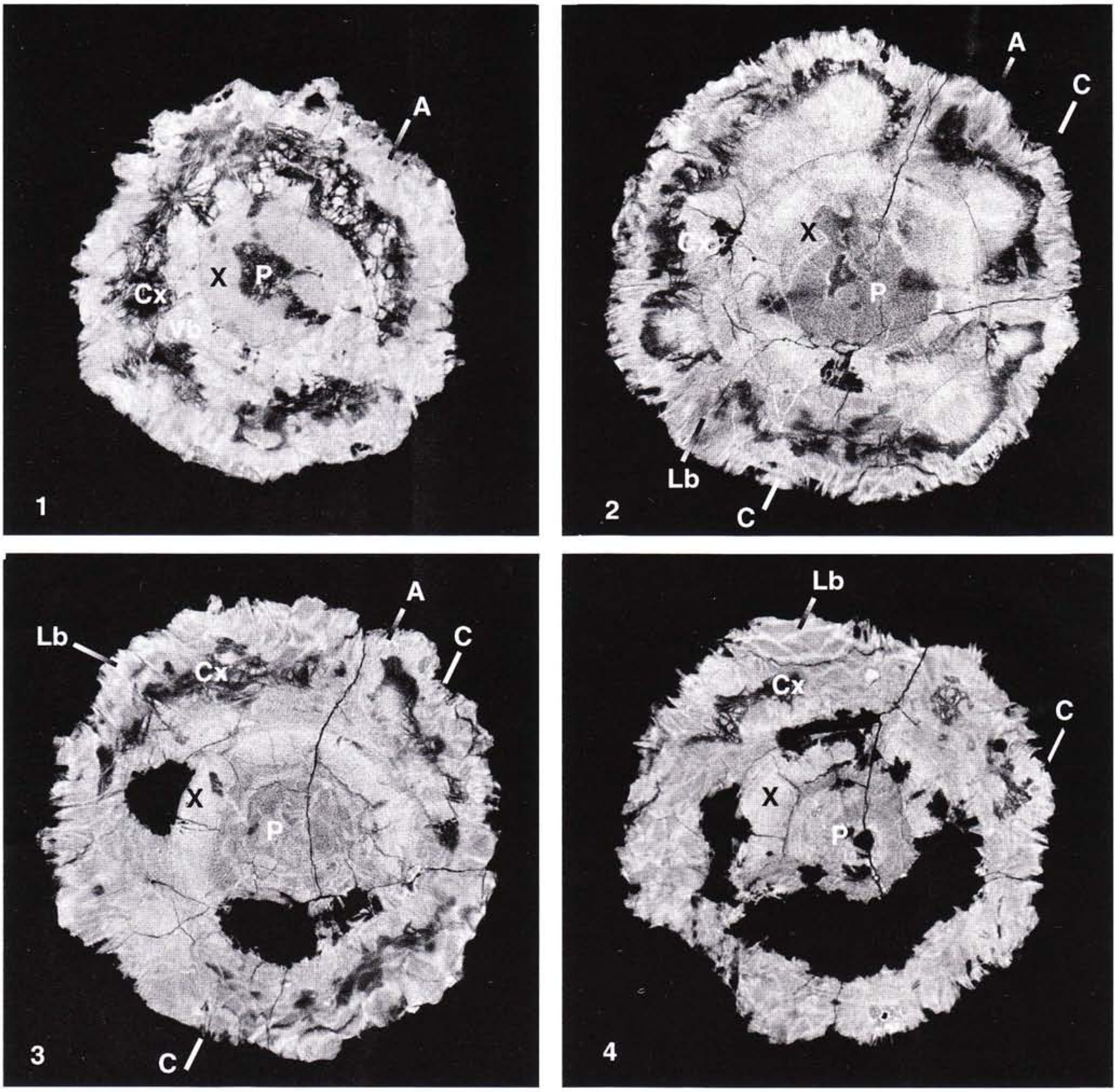


Fig. 3 - CT of transversal cross sections through the trunk of *Cycadeoidea* sp. (1) Cross section through the lower part of the trunk (20 mm from the base) with pith (P), xylem (X), cortex (Cx) with vascular bundles (Vb) and the armour (A) as the outermost layer. Some crystallization structures are recognizable in the cortex area. Leaf bases (Lb) and remains of floral cones (C) are visible only in the middle part of the trunk surface (see below). (2) Cross section through the central part of the trunk (51 mm from the base) with pith (P), xylem (X), and vascular bundles (Vb). Leaf bases (Lb) and remains of cones (C) are clearly visible. Cracks and holes are recognizable as dark lines and irregularly formed black areas respectively. (3) Cross section through the upper part of the trunk (70 mm from the base) with pith (P), xylem (X), cortex (Cx) with vascular bundles (Vb) and armour (A). Some floral cones (C) are clearly marked by the displaced vascular bundles of the surrounding leaves. (4) Cross section through the uppermost part of the trunk (80 mm from the base). Pith (P) xylem (X) and cortex (Cx) are strongly fragmented whereas the leaves bases (Lb) and cones (C) are well preserved. The black open cracks and holes give an impression of fragility.

sunken. The peduncle itself is not preserved on the studied specimens. The protruding helically arranged cone-bracts (Br) are well preserved over most of the surface. Details like the openings of the resin canals on the bracts are clearly recognisable with a hand lens. Due to abrasion caused by transport the distal ends of the seeds (S) are exposed on one side in the proximal part of the cone. The seeds seem to sit rather loosely within the ovuliferous scales leaving an open space between the sclerotesta (Sc, see below) and the surrounding tissue.

The CT pictures give a good overview of the morphology of the cone (Fig. 6). The central longitudinal section (Fig. 6.1) shows a relatively dark area near the insertion of the peduncle, which represents the basal

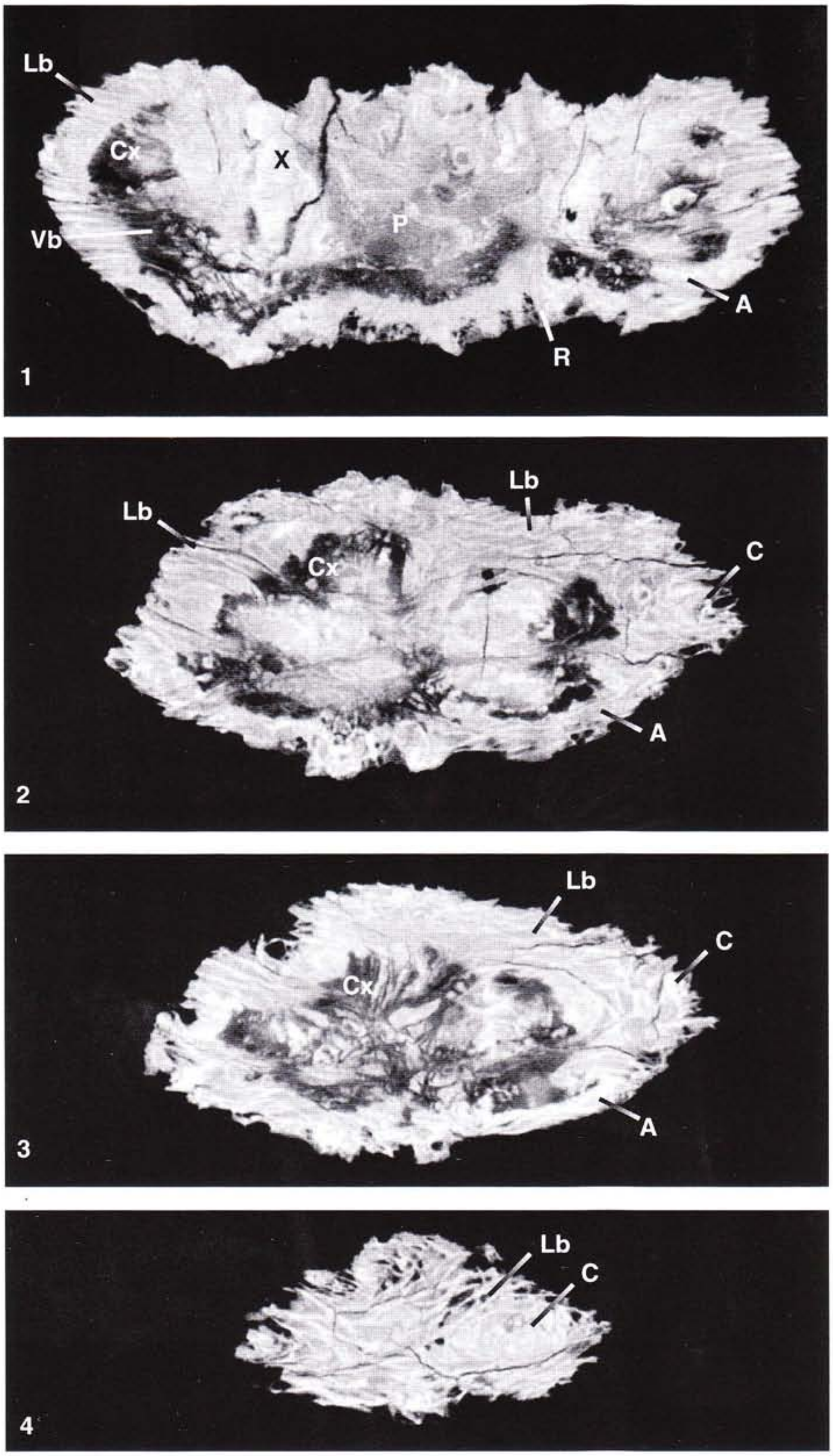


Fig. 4 - CT of longitudinal cross sections through the trunk of *Cycadeoidea* sp. (1) Cross section (140 mm from the outer surface) with the pith (P) in the center, the xylem (X), the cortex (Cx) with vascular bundles (Vb) of the leaves and the peduncles and the brightly contrasted armour (A) with clearly visible leaf-bases (Lb). The structures in the youngest parts of the trunk including the growing zone are corroded. (2) Cross section (210 mm from the outer surface) through the armour (A) and the outer part of the cortex (Cx) with vascular bundles (Vb), leaf bases (Lb) and the remains of one cone (C). The bright areas within the cortex represent the vascular bundles of the peduncules and the leaves. (3) Cross section (220 mm from the outer surface) through the armour (A) and the outer part of the cortex (Cx) cutting leaf bases (Lb) and several peduncules approximately perpendicularly. A quite well-preserved floral cone (C) is cut almost radially. (4) Cross section (240 mm from the outer surface) through the armour (A), showing leaf bases (Lb) and cutting through a cone (C).

part of the pith (P). The pith itself is extended in the central area of the cone. It is clearly recognisable by its relatively homogenous granular structure produced by the large cells. The form of the rather thin-walled cells is beyond the resolution of the CT. The xylem (X) surrounding the pith is marked by a brighter area and by some almost continuous lines running parallel to the surface of the pith. These lines represent vascular bundles (Vb). Some branching of the vascular bundles to the peduncles of the bracts (Br) and to the ovuliferous scales (Os) can be clearly seen. The intense contrast between the dense sclerotesta (Sc) of the seeds (S) appearing in white and the black area representing an open space around the distal end of the seeds, produce the most distinctive feature of the CT. The inner part of the seeds is of a medium grey colour. On the CT images on Fig. 6 some seeds show central dark grey shadows which are considered to represent fragile and originally unlignified structures (E: embryos). An almost ideal central section of a seed cuts through the nucellus and the megagametophyte. In the peripheral portion of the cone the dark grey radial lines represent

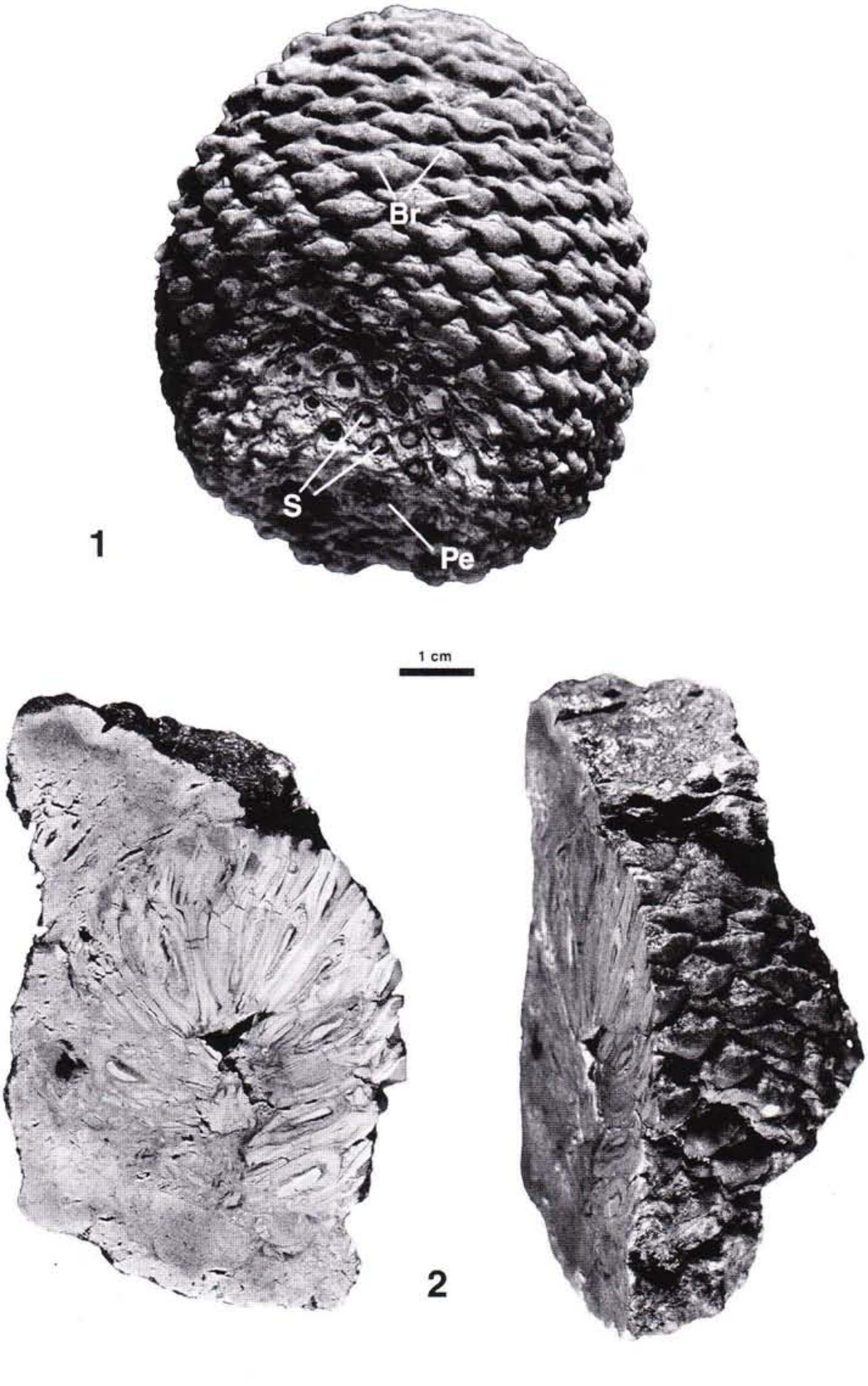


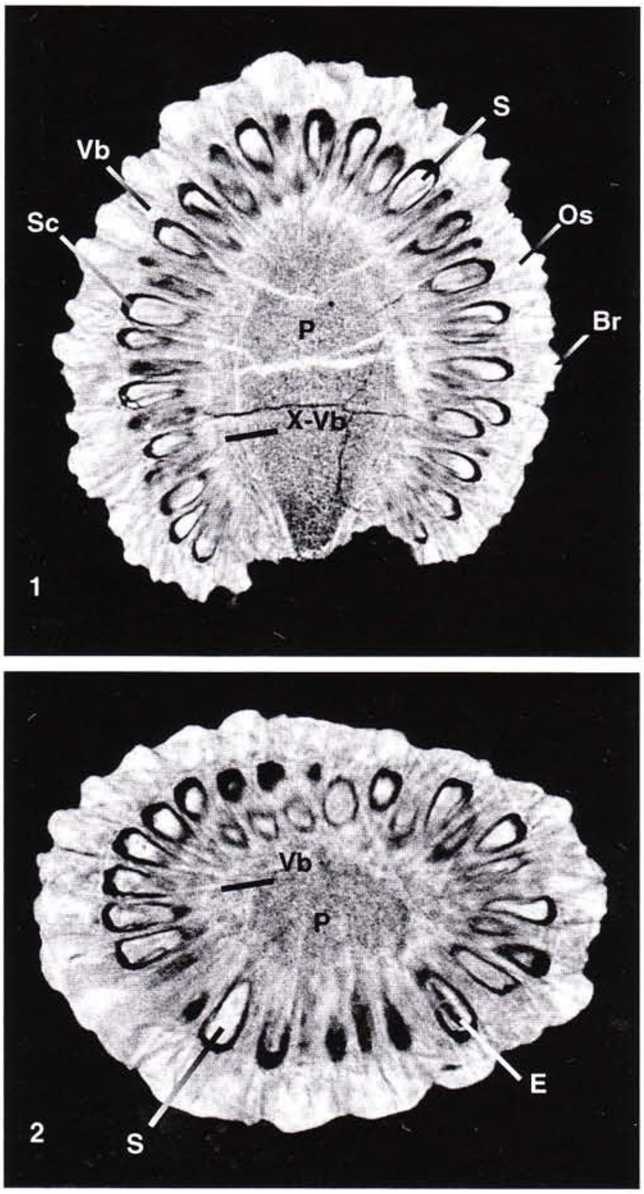
Fig. 5 - Silicified cones of *Araucaria mirabilis* (Spegazzini) Windhausen, from the Cerro Cuadraro Petrified Forest in Patagonia (Jurassic), Argentina. (1) Perfectly preserved specimen to which CT has been applied. Br: bracts, Pe: peduncle, S: seeds. (2) The specimen used to prepare the thin section (cf. Fig. 7) cut into two pieces.

vascular bundles. The strongly lignified parts of the bracts are almost white.

Some artifacts are recognisable in the cone. The white irregular lines running across the pith and extending into the woody cylinder represent old, completely sealed cracks (Fig. 6.1). The dark lines visible in the lower part of the cone cross at least one white line. They can be interpreted as a younger generation of cracks which could still be partly open.

The transverse section (Fig. 6.2) at a relatively proximal level shows the irregular surface of the cone with the flattened part towards the top. Except for the left and right sides of Pl. 6, fig. 2, the entire surface seems to be smoothed by abrasion. The structures discernible in this section are similar to those discussed in the central longitudinal section. The granular structure of the pith (P) is clearly delimited from the brighter part of the xylem (X) which shows well-differentiated cross-sections of the vascular bundles (Vb) and a few radially oriented bundles branching towards the peduncles of the ovuliferous scales (Os) and bracts (Br).

For comparison a second, less completely preserved specimen, has been cut and sliced for a thin section (Fig. 7). This specimen is perfectly suited to compare the resolution of the CT with the actual preserved structures. The surface of this cone is strongly corroded, the originally protruding bracts are partly abrased. Although the innermost and lower portion of this cone has been dissolved or broken, we can assume that in its well preserved distal parts it corresponds to the complete specimen used for CT. The morphological details recognisable in the thin section (Fig. 7) are closely comparable to the superb specimens illustrated by Stockey (1975, 1978). The most obvious features are the bracts (Br), the seeds (S) with the dense structure of the integument (I) and the brightly contrasted resin canals (Rc). Rather small and fragile structures such as the micropyle (M), the nucellus (N) and the embryo (E) can also be distinguished in Fig. 7. The two minute grooves located adjacent to the nucellus might in fact represent the archegonia (Ar). Cellular structures are best discernible in the distal portions of the bracts.



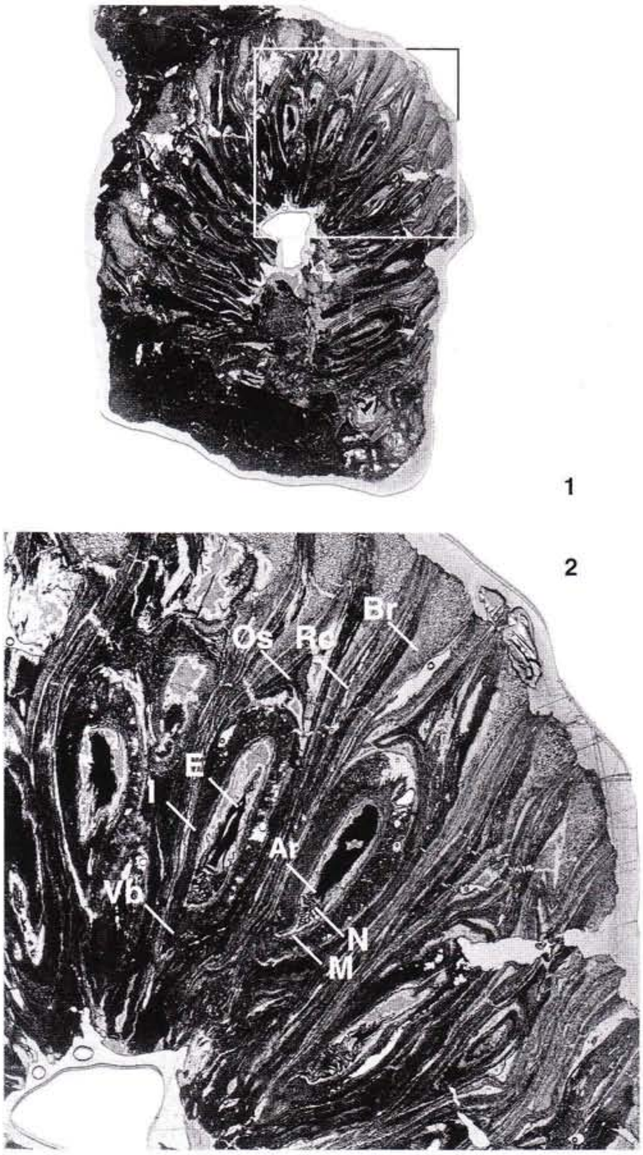


Fig. 6 - CT of central longitudinal section and median transverse section through the seed cone *Araucaria mirabilis.* (1) The central longitudinal section (19 mm from the base) shows the central pith (P), xylem (X) with vascular bundles (Vb), and the seeds (S) with sclerotesta (Sc) embedded within the ovuliferous scales (Os). The white lines originating from old cracks appear to be completely sealed. A younger generation of possibly open cracks (dark lines) are recognizable in the lower part of the cone. (2) The median transversal section (33 mm from the base) shows pith (P), xylem with zone of the vascular bundles (Vb), seeds (S) and ovuliferous scales. The dark line in the median cross section of one seed represents an embryo (E).

Fig. 7 - Thin section of a second specimen of *Araucaria mirabilis.* (1) Thin section through the cone. Note the incompletely preserved lower part. (The rectangle indicates the area of the detailed view shown in Fig. 2. (2) Detail of thin section with longitudinal sections of seeds, ovuliferous scales and bracts (Ar: archegonia, Br: bract, E: embryo, I: Integument, M: micropyle, N: nucellus, Os: ovuliferous scale, S: seed, Rc: resin canal, Vb: vascular bundle). The thin section has been scanned directly with a Leitz photo scanner.

Conclusions.

The present study shows an application of CT to palaeobotanical objects. As a main advantage this method allows observation and reconstruction of fossil specimens in three dimensions. Traditionally, similar results could be obtained only by numerous sections leading to fragmentation or to an almost complete destruction of the specimens. This new technique is capable of producing global views through relatively large objects (eg. trunk) and it is very well suited for diagnostic purposes prior to conservational work. It can also be applied prior to detailed analyses which would involve the destruction of the object. However, when compared to commonly used analytical methods (thin sections, serial cuts) the resolution of the CT is limited. It is a relatively rapid method to study whole series of specimens which could lead to a better understanding of the growth and architecture of plants and possibly to the differentiation of species.

Compared to the extraordinarily well-preserved detailed sections of the silicified *Cycadeoidea* published by Wieland (1906), the trunk of the collection appears to be poorly preserved. However, to our knowledge the presented images are the first to show an entire trunk sectioned in series and in several directions. The comparison of the CT image (Fig. 6) of *Araucaria mirabilis* with the thin section of a similarly well-preserved specimen (Fig. 7) clearly demonstrates that the details recognisable in the sliced specimen (eg. cell structures) are beyond the resolution of the CT. However, the non-destructive CT technique is the best tool to visualise internal features of rare and possibly unique fossils. Furthermore, since the digital information generated by CT is stored in standard exportable file formats, the data obtained in this way may be manipulated and sequential sections can be linked to create 3D-models or animations.

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