Hidden Structure of Fossils Revealed by Neutron and X-Ray Tomography

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Abstract. In the past, meaningful information about the internal features of plant and animal fossils has only been accessible through the application of irreversible destructive procedures to rare and in many cases irreplaceable fossils. Now, neutron tomography (NT) complemented with X-ray computer assisted tomography (CT or CAT-Scan), both Non-Destructive Examination (NDE) techniques, can be applied as research tools for detecting and visualizing hidden and unknown structures of plant and animal fossils, especially when they are embedded within a rock matrix. These analytical tools, available at the SANRAD facility of the SAFARI-1 nuclear research reactor in South Africa, have recently been used to investigate several palaeontological specimens. The success of both analytical techniques, in the scanning of a variety of plant and animal fossils, was found to be heavily influenced by the type of fossil preservation and the chemical composition of the matrix and its density. Furthermore, objects could not exceed ~ 20cm in diameter due to excessive attenuation of the incident radiation. In this paper the findings of the latest research, utilizing X-ray- and neutron tomography as analyzing tools, on several plant and animal fossils are discussed.

INTRODUCTION

The facilities and expertise offered to South African and international scientists at the SANRAD facility of the SAFARI-1 nuclear research reactor at Necsa, 30km from Pretoria, South Africa, provide a wonderful opportunity for palaeontologists to explore the potential of non-destructive examination techniques. The application of neutron and scanning radiography and tomographic reconstructions to palaeontological subjects is a very exciting prospect, and this preliminary investigation has provided important information regarding the value of these techniques to palaeobotanical studies. Tomographic procedures provide non–invasive three-dimensional (3D) visualization and characterization of objects from transmission data [1].

The success of x-ray and neutron tomography scanning of a variety of plant and animal fossils was highly variable, and was shown to be heavily influenced by the type of fossil preservation and the size of the specimen. Subjects could not exceed approximately 20 cm in diameter because of size restrictions imposed by the equipment and the chemical composition and density of the matrix which had a huge effect on the success of the scanning as experienced by Schwartz et. al. [1] when utilizing either X-rays or neutrons in imaging various types of fossil samples. Each sample (specimen) which is embedded

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in its own matrix with its own density is a unique case to be either solved by X-ray or neutron imaging and only through experimentation utilizing and comparing both radiation imaging techniques.

South Africa has a huge fossil heritage in the Karoo area in the central part of the country, in addition to the world heritage sites at Swartkrans and the Sterkfontein caves at Krugersdorp at nearby Necsa. Unesco has declared the Sterkfontein area outside Johannesburg as a World Heritage Site because of its rich palaeontological heritage which rivals that of the famous East African sites. [2]

Previous preliminary studies undertaken at the SANRAD facility on archaeological samples include a study of the parietal, frontal and occipital bone areas of the cranium bone of *Australopithecus africanus*—(Mrs. Ples) with the film technique [3][4].

The aims of this research were to explore neutron and X-ray radiography and tomography to assess the value of these techniques in palaeobotanical and vertebrate palaeontological studies through examination of:

1) Impression plant fossils of ovulate glossopterid fructifications formerly assigned to the genus *Hirsutum*, in the hope of detecting structures known to extend beneath the surface of the rock matrix. Detection of these structures would obviate the need for destructive methods to demonstrate their presence.
2) Specimens of the enigmatic plant genus *Breytenia*, to facilitate a better understanding of the arrangement of their internal structures.
3) Animal fossil specimens of therocephalians, cynodonts and therocephalians (mammal-like reptiles) to explore the nasal and cerebral cavities without destroying most of the specimen through destructive methods.
4) Vertebrae and limb fossil bones of an archosaur reptile to discover the cause of death.

1. EXPERIMENTAL FACILITIES

The X-ray / neutron radiographs / tomographs for this study were obtained at the SAFARI-1 research reactor, which is located at Pelindaba, 30 km west of Pretoria, and operated by NECSA [5]. The reactor was commissioned in 1965, has a design power of 20MW and provides a neutron flux of 1.2 x10^7 n.cm^{-2}.s^{-1} at beam port no-2 at the object under investigation while a 100kV W-anode continum X-ray machine was installed for X-ray imaging. The object being imaged is located in front of a neutron scintillating screen (6LiF/ZnS:Cu.Al,Au) and replaced by an X-ray scintillating screen (Gd-OS) when X-ray tomography is required. The specimen is placed onto a rotation table (Figure 1) for multiple image capture (up to 200 projections) in a 180 degree rotation mode for neutrons and > 200 projections in 200degrees for X-rays. An Al-coated front surface mirror reflects the image formed on the scintillator screen away from the radiation beam onto a Peltier-cooled ANDOR - CCD-camera system containing a 1024 x 1024 pixel array CCD chip. Image noise is reduced by cooling the camera chip up to -45ºC as well as through background image (open beam without sample) and dark current noise subtraction. The 16-bit dynamic range image (radiograph) is recorded (captured) by integrating onto the

CCD chip and then readout to a frame grabber—25 sec for neutrons and 1.2 sec for X-rays. Highest spatial resolution (200 micron) was obtained for most of the samples utilizing a lens with maximum 9cm x 9cm field of view onto the scintillator screen.

For neutron reconstruction, IDL software was used while for the X-ray tomography reconstruction, OCTOPUS reconstruction software was utilized for the X-ray cone beam reconstruction of the specimens.

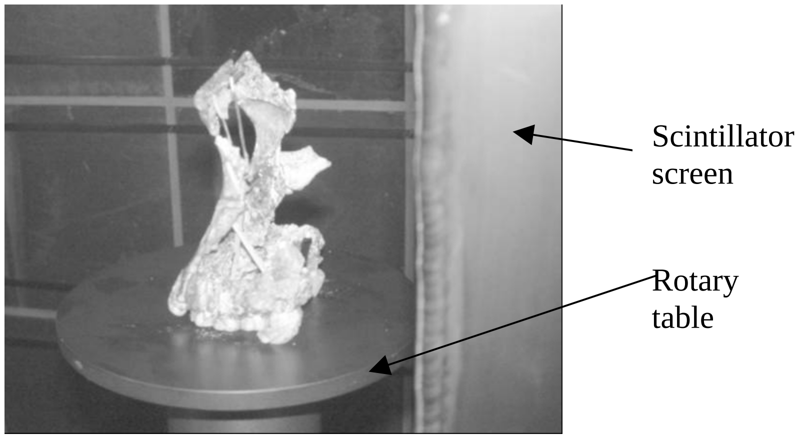

FIGURE 1. *Fossil placed on rotary table.*

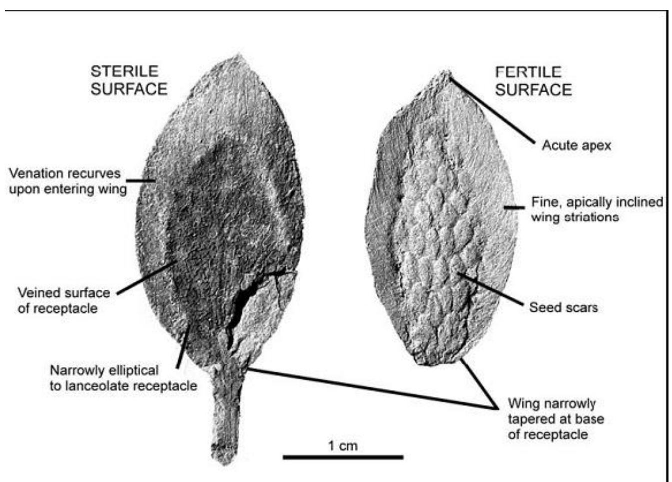

FIGURE 2. *'Typical' examples of impression fossils showing the sterile surface (BP/2/13979) and fertile surface (BP/2/13964) of H. intermittens, illustrating the diagnostic features of the species as described by Anderson & Anderson (1985). [6].*

2. RESULTS AND DISCUSSION

2.1. Palaeobotanical Applications (Plant Fossils)

2.1.1. Hirsutum intermittens from Vereeniging

Hirsutum intermittens was also shown recently to have a complex wing structure [6] with a double wing (see Figs 2&3). The so-called primary wing tapers at the base of the

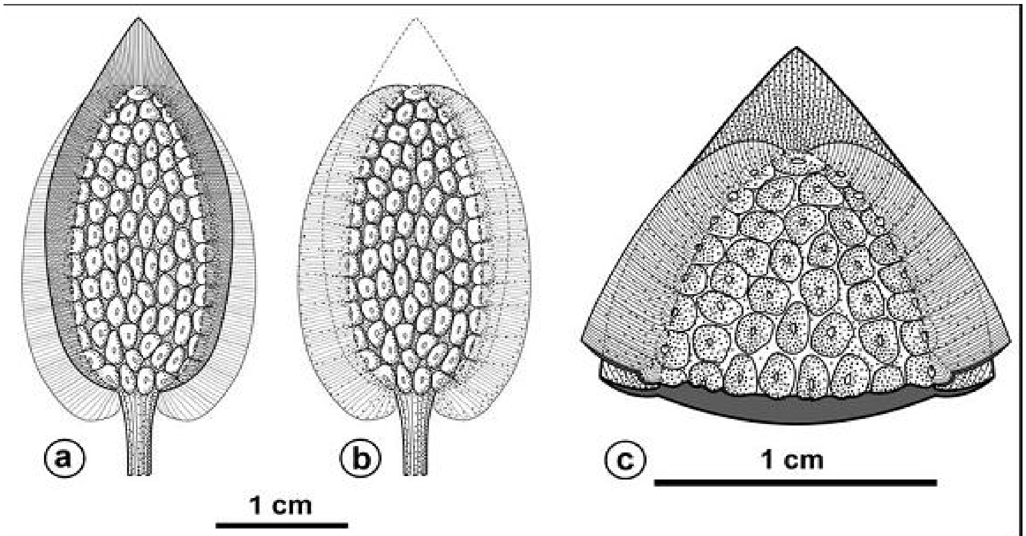

FIGURE 3. *Proposed reconstructions of (a) Hirsutum intermittens with the primary or hirsutoid wing exposed and (b) with the secondary or scutoid wing exposed, and (c) a reconstruction of the apical portion of the fructification indicating the positions of the two, superposed wings relative to the receptacle. [6].*

fructification, and is extended into a pointed tip in the apex (Figure 2). The secondary wing lies at a slightly lower level in the matrix in impressions of the fertile surface of the fructification. It is contracted (tapered) at both the apex and the base of the fructification, with rounded basal lobes. It may be broader than the primary wing in the medial portion of the fructification. X-ray radiography was performed on a specimen of *H. intermittens* in an attempt to reveal the secondary wing underlying the surface impression of the primary wing of the fructification.

Penetration by the x-rays through the thin slab was excellent, but the resolution of the images was inadequate (see Figure 4). The wedge of sediment separating the two wings along the periphery of the fructification is extremely thin, and the secondary wing itself appears to be a very thin, fine structure.

2.1.2. Breytenia fructifications

2.1.2.1. Background

Melville [7], named these structures *Breytenia plumsteadiae* in acknowledgement of the Breyten Colliery where they were found. Melville was convinced that *Breytenia* was a glossopterid fructification, and that it was on a direct evolutionary path to the angiosperms. He considered the fructification to be an enclosed structure with thick fleshy walls and a narrow, tubular terminal orifice, bearing numerous playspermic seeds within a central cavity.

The *Breytenia* fossils are preserved in a very unusual manner. They are not impression or compression fossils, but appear to be partially permineralised. They are composed of a delicate arrangement of internal cavities with permineralised walls, and are enclosed by a thick outer wall with a peculiar mamillated surface texture.
These fossils proved to be ideal candidates for neutron- and X-ray tomography, techniques that most effectively revealed the internal organisation of the fructification. This new information will contribute greatly to the thorough revision and re-description of these fructifications in the near future.

However, although these preliminary results are inconclusive, they are encouraging. A hint of the secondary wing is visible in several of the tomographic slices (Figures 4 c and d). A system capable of higher resolution scanning may prove to be extremely effective in future studies of plant impression fossils.

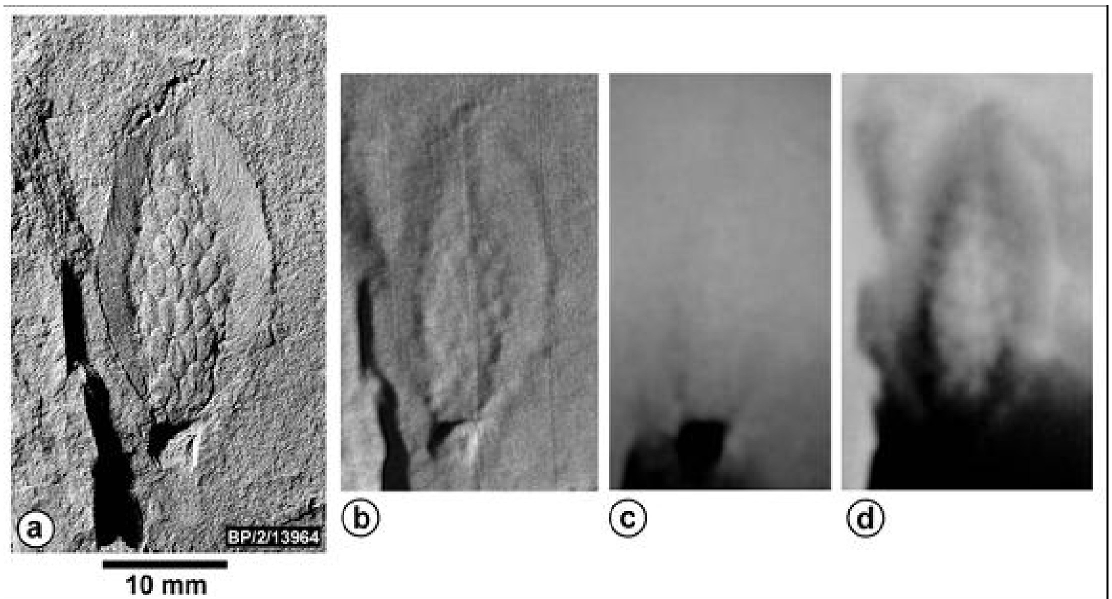

FIGURE 4. *(a) Photograph of a specimen of Hirsutum intermittens; (b) tomographic reconstruction of the specimen from x-ray scans; (c) & (d) frontal tomographic sections through the specimen just below the slab surface.*

Neutron scanning:
Neutron scanning differentiated two tissue types within the specimen, with strong attenuation of neutrons by the surrounding coal matrix. Resolution of the images was low, but the shape and orientation of the internal chambers was apparent (Figures 5 b-f).

X-ray scanning:

Excellent results were obtained using x-ray scanning and tomography (Figures 5 g-n). The resolution was significantly better than that obtained during neutron scanning. There was also a greater differentiation of tissues within the fructification. The shapes and orientation of the cavities and internal structures was very clearly depicted. X-rays passed through the coal matrix with very little attenuation, but there was a strong differential between the thick, outer, amorphous layer of the fructification and the central, cavity-filled zone. The thick outermost layer attenuated the x-rays to a higher degree.

The pedicel (stalk) of the fructification was not visible on the surface of the specimen, but was clearly apparent in the tomographic sections (Figures 5 g and j). The approximate size of the pedicel was measured across sequential sections, and found to be 0.36 mm thick.

2.2. Palaeontological Vertebrate Applications

Two main lines of interest are centered on the use of neutron tomography as a non-invasive technique for the study of material from the Karoo area in South Africa.

Firstly, the tiny skull of a small therocephalian (mammal-like reptile) that is encased in sediment was selected (Figure 6). In cases such as this a neutron tomography scan is conducted to assess the condition of the specimens inside the sediment, to assist with decisions regarding the mechanical removal of the matrix for detailed study. Secondly, the nasal and cerebral cavities in specimens of therocephalians and cynodonts were explored. The aim was to gain access to details of the inner anatomy of the skulls, particularly to locate turbinal bones in the olfactory cavity and to get a close view of the cranial cavity surrounding the brain and ear structures.

In the specimen of *Hofmeyria*, sediments and bones of the skeleton are covering the ventral side of the skull and then it is not possible to see any structure of the palate. Exterior mechanical prepartion is not possible because it will mean destruction of the other bones. However, X-ray and neutron scanning techniques exposed many of the otherwise hidden features of the palate. (Figures 7, a, b and c] In most of the vertebrate fossils of the Karoo the upper jaw is laterally covers the lower jaw, obscuring the teeth of the lower jaw. With scanning, it was possible to assess the number of postcanine teeth on the lower jaw of both *Hofmeyria* specimens. Unfortunately evidence of the turbinal bones in the nasal cavity and details of the inner ear have not been recognized in the scanned material thus far.

2.2.1. Bone pathology on an archosaur reptile

Archosaurs are a large group of reptiles that originated in the Latest Permian, more than 250 million years ago, and predominated during the whole Mesozoic era [9]. They gave origin to several reptile groups including crocodiles, dinosaurs and birds. The goal of this study was to discover the cause of death of an archosaur of the Early Triassic age (approximately 245 million years old) from the South African Karoo.

CONCLUSIONS

Neutron and x-ray radiography and tomography are powerful tools, with enormous potential in the palaeontological arena. Accessing information about the internal features

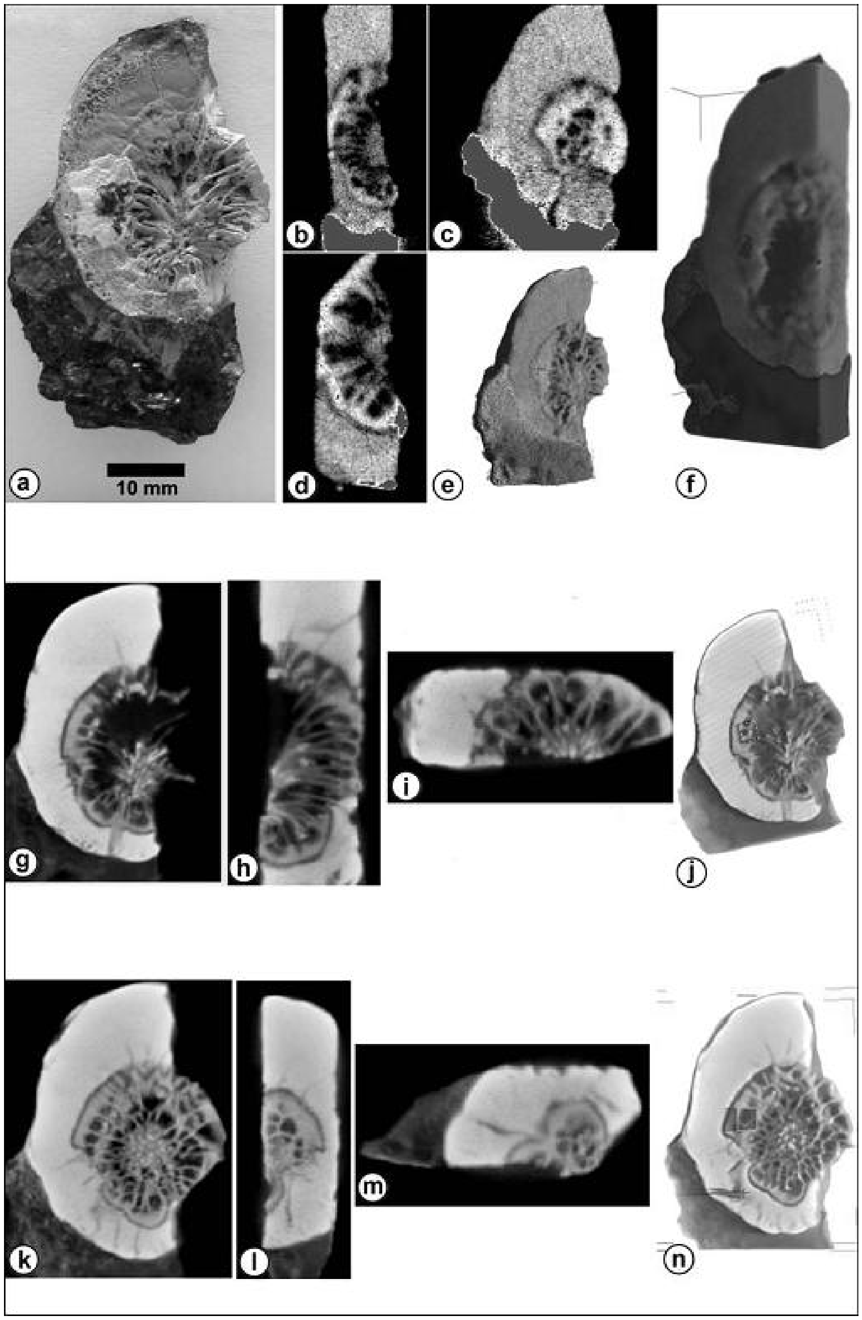

Figure 5. *(a) Breytenia pumsteadiae: (b)-(d) tomographic sections compiled from neutron scans, in longitudinal, frontal and transverse section respectively; (e)&(f) tomographic reconstructions from neutron scans; (g)-(i) frontal, longitudinal and transverse sections from x-ray scans; (j) 3-D tomographic reconstruction; (k)-(m) frontal, longitudinal and transverse sections from x-ray scans; (n) 3-D tomographic reconstruction slice.*

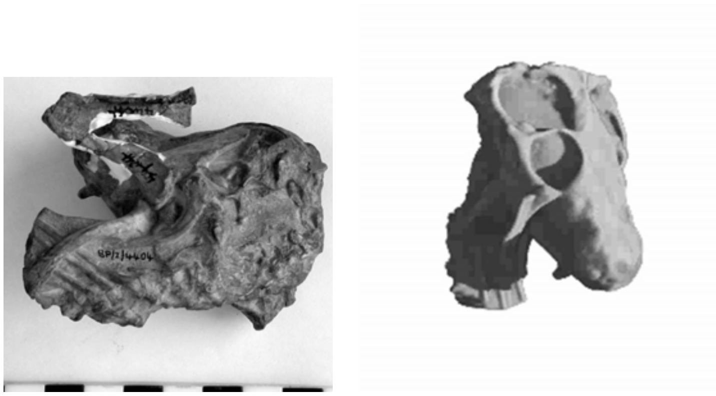

Figure 6. *(a) Hofmeyria; (photo left) and (b) its neutron tomograph reconstruction (Right).*

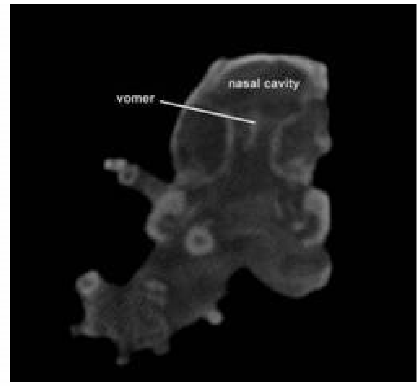

Figure 7a: *Sagittal slice through tomograph of animal fossil.*

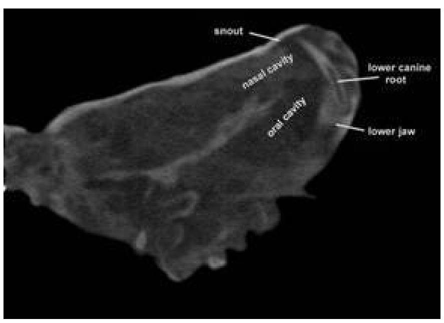

Figure 7b: *Axial slice through tomograph of animal fossil.*

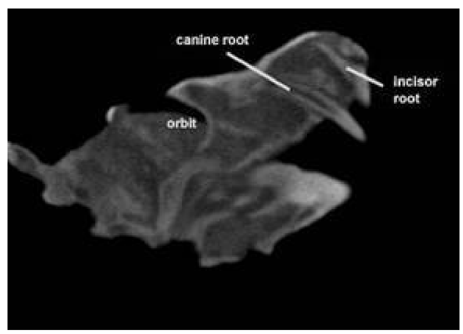

Figure 7c: *Frontal slice through tomograph of animal fossil.*

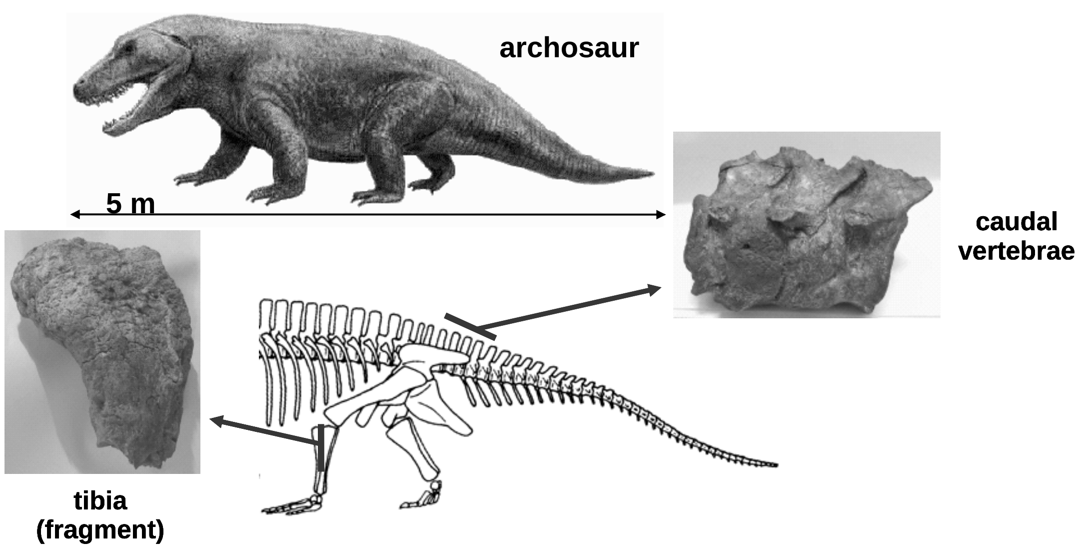

Figure 8. *Archosaur reptile with tibia and vertebrae sections investigated with neutron tomography [Illustrations from Cox et al. 1999 and Gower 2003].*

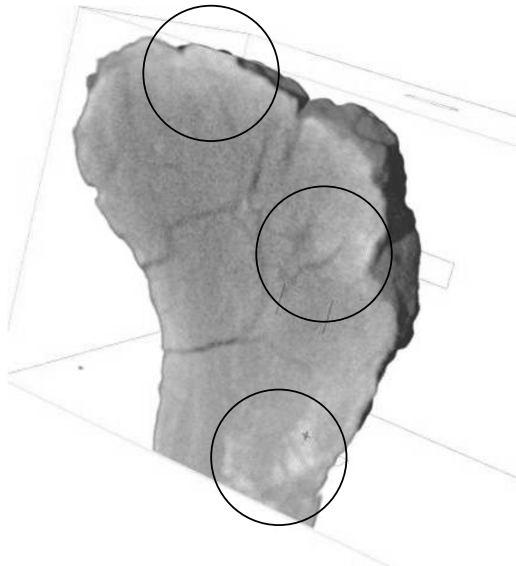

Figure 9. N*eutron tomography slice of tibia fragment from Archosaur animal fossil.*

of both plant and animal fossils has always been a serious problem for palaeontologists. In the past this information has only been accessible through the application of destructive procedures which result in non-reversible damage to rare and in many cases, irreplaceable fossils.

Radiography can allow scientists to observe features otherwise obscured by the rock matrix or exterior features of a fossil. Unfortunately, the resolution of the images obtained at SANRAD proved to be the greatest limiting factor in the study of the plant impression fossils. These fossils represent extremely narrow cavities within the rock matrix, and the resolution was, in most cases, insufficient to allow even for their detection.

Very dense permineralised fossils, are probably not suitable subjects for radiography, but scanning of thinner, smaller specimens such as the *Breytenia* specimens, can be very successful. The *Breytenia* specimens proved to be excellent subjects for radiography, as they contained numerous cavities which showed up in stark contrast to the enclosing permineralised tissues.

The varied results obtained during this preliminary investigation, illustrate the need for further experimentation with fossils of different preservation types. Radiographic techniques will undoubtedly play an increasingly important role in all branches of palaeontology, particularly as the imaging and scanning technology improves, and as palaeontologists establish which types of fossil material are best suited to this method of investigation.

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