Mummification unwrapped: investigating an Egyptian votive mummy using novel, non-invasive archaeometric techniques

Carla A. Raymond BA BSc

Department of Earth and Planetary Science

Faculty of Science and Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Research

Submission Date	19/10/2017
Corrections Submitted	06/02/2018
Corrections Accepted	12/02/2018
Print Date	15/05/2018

ansto

Dr Joseph Bevitt

Australian Synchrotron

Dr Chris Hall and Dr Anton Maksimenko

Australian institute of ARCHAEOLOGY

Dr Christopher J. Davey

MMI MACQUARIE MEDICAL IMAGING

Prof. John Magnussen

"Inside every mummy is a story waiting to be told"

- Mummies of the World exhibition, 2017

Table of Contents

List of Figures

List of Tables

List of Supplementary Materials in Appendix

Statement of Originality

I certify that, to the best of my knowledge, the work presented herein is the original work of myself, the author, and has not been presented or published elsewhere. All published works and work carried out by persons other than the author presented here are appropriately referenced and due respect given to the participants. As such the following people contributed to the production of this thesis, via the supervision of, or direct collection of data:

Dr Timothy Murphy, *MQGA*	The samples analysed using SEM and Raman were undertaken within the microscopy laboratories at Macquarie University GeoAnalytical, Sydney, under the instruction and supervision of Dr Timothy Murphy.
Beta Analytic Inc., *commercial collection*	Radiocarbon dating, was done commercially and therefore with no direct input from the author.
Professor Damian Gore, and Russell Field, Department of Environmental Sciences, Macquarie University.	X-ray Diffraction data collection was completed in collaboration with the author and all interpretation of XRF data is that of the author.
Prof John Magnussen, *Macquarie Medical Imaging*	X-Ray CT data were collected under the supervision of and in consultation with the author. Interpretation in the context of this study is wholly that of the author.

Further no part of this thesis has been presented, accepted or been published for the award or consideration of a higher degree or diploma at this or any other educational institution.

19/10/2017

Carla Raymond, Ba.BSc.

Author, MRes Candidate.

Acknowledgements

To my supervisors, Associate Professor Simon Clark, Dr Joseph Bevitt, Dr Yann Tristant, and Dr Ronika Power, how can I ever thank you enough for giving me this unique opportunity. You have been the most amazing team of mentors and I am incredibly grateful to each and every one of you for challenging me to try harder, and inspiring me to be relentless in pursuing my aspirations.

Simon, thank you for your guidance throughout my Masters of Research program, for helping me to undertake new projects last year, that ultimately prepared me for the start of this research thesis. Without your enthusiasm and connections, this project may never have come together. You arranged for this team to meet almost two years ago, and I'll never be able to thank you enough for this opportunity, it has been such a wonderful experience. Your advice and mentorship has challenged me to really push the frontiers of archaeological research from a science perspective, and consider all the areas of impact that this project can have across disciplines.

Joseph, I don't know what to say. Thank you. You may never fully know the impact your work has had for me. I am grateful to you for taking the time to take a fledgling masters student under your wing for an internship, to give me a chance to explore and pursue my passion. Thank you for remaining calm in the face of the many obstacles faced throughout this thesis, you helped me to keep things in perspective and focus on the things I could control rather than those I could not. You have been endlessly supportive, all the while navigating the constant challenges and responsibilities of your own work. Your unremitting work ethic and your enthusiasm is inspirational, and I hope that we can continue to work together in the future.

Yann, merci beaucoup pour tout. I have really valued your support and guidance the whole way through this thesis project. You have been critical, yet encouraging, providing insight and expertise wherever you could. Thank you for showing genuine care and concern for how I was going when I got confused or discouraged along the way. Your constant positivity and passion has been instrumental in helping me keep my eyes on the goal, and to remember why I took up this project in the first place. Thank you for taking the time to be involved in this project and I look forward to future projects together.

Ronika, you have been an inspiration to me from day one. I am constantly encouraged by seeing a woman as driven and passionate as yourself in our field, your strength and determination is exceptional. I have really appreciated your boundless enthusiasm and support in this thesis project, your input and expertise has been invaluable. Thank you also for connecting me to so many incredible people, such as John and Tyr, who have greatly enriched this thesis project with their contributions. I have thoroughly enjoyed working with you, and would love to collaborate on more projects where possible.

To Dr Christopher Davey, I would like to say thank you for entrusting such a precious, curious artefact to us for this thesis study. There were many uncertainties about the artefact, and I am grateful that you gave us an opportunity to study a mummy in a way no one else has. Thank you for showing me around the Australian Institute of Archaeology when I visited Melbourne in the early days of this project, and for the important work you do there as the curator of the collection.

To Professor John Magnussen, it has been wonderful to have you as part of this team. I really appreciate your genuine interest and willingness to help us X-ray a mummified cat in your medical imaging unit, I think that the staff as well as our team found that to be a very exciting day. Thank you for your patience and correspondence with me about my methods and results, taking the time out of your busy schedule to ensure that I interpreted the data correctly.

To the IMBL team at the Australian Synchrotron, especially Chris Hall and Anton Maksimenko, thank you for sponsoring me to attend your workshops in March 2017. I gained a lot of valuable knowledge about how to process my data using a number of different software packages, and what potential the synchrotron holds for future archaeological investigations.

To Dr Tyr Fothergill, and Dr Jana Jones, thank you for replying to my email queries, and being so willing to share your insights. I am very grateful that you took the time to take interest in my thesis project, and gave me direction to further references to help better my understanding of what you shared. I have learnt so much, across so many areas in this project, so thank you for your contributions.

To Professor Paul Haynes and your team, thank you for your involvement in this investigation. Although things didn’t go quite as we had hoped, I appreciate your willingness to help me, and to take a chance, even when the outcomes were uncertain.

To Professor Damian Gore and Mr Russell Field, thank you for examining my samples with XRD. It was good to include this technique and it was informative also. Thank you for taking the time, I know you are both very busy, so it was greatly appreciated.

To Dr Tim Murphy, I want to thank you for the time you invested to help me get the results I needed. Thank you for letting me bug you constantly to get data, and for being a sounding board for my ideas and questions. Your enthusiasm and many stories made data collection quite enjoyable, so thank you.

To my MQ family, you know who you are, thank you for keeping me sane this year. Having such a great group of friends to go through this thesis journey with has made all the difference. I'm so proud of all of us! Special thanks to Bruno, for the quality banter, and unofficial French lessons when I needed to translate a paper. And a special thank you to Lanati, for being such a support this year, even if it was just getting away for a coffee and some fresh air, I really appreciated it.

To Anita, Sean, and Aidan, thank you for sticking by me and putting up with me being so unavailable and tired, I have really appreciated you being so understanding. Thank you for being supportive, encouraging and my own personal cheer squad all the way through, that has helped me more than you can know. I hope I can be there to return the love and support you have shown me whenever you need me.

To Finn and Mitch, I could not have made it without you both, that goes for undergrad and postgrad. I count myself so lucky to have met you both. You have been serious anchors for me in my difficult times over the years, thank you for always having my back. Finn, thank you doesn't really begin to cover it. Thank you for the countless coffee breaks, the gym-sessions-turned-therapy-sessions, and tough love when I needed it, you have helped me immensely to keep things in perspective, and to keep trying even when it all seems too much. Mitch, thank you for your encouragement and for always bringing a smile to my face. Your guidance and advice, as someone who has been here before, has been invaluable and I'm very grateful.

Mum and Dad, thank you for always encouraging me that I could do anything I put my mind to, and for living by example. Thank you for all the sacrifices you have made to get me to where I am today, I can never repay that generosity and kindness. Mum, thank you for sticking with me through the breakdowns and the rough times, even when I wasn't the nicest person to be around. Dad, thanks for the hugs, for driving me to uni on countless occasions, and for keeping me well fed throughout this year, you kept me going. I hope that I have made you both proud parents.

Thank you, family, for your unconditional support and love throughout this year, it means the world to me. Wesley, I miss when we used to catch up here on campus for lunch, I really enjoyed sharing my uni years with you. Although you've been further away than I'd like this year, thank you for always being a listening ear, for being there for me, and for being my best friend. Joel, thank you for the banter, the sing-alongs, the laughter and for understanding the shared stress of our respective theses. You're one of a kind Joel, and you're truly inspiring to me, making me feel like I can always do and achieve more.

Glossary and Abbreviations

Coccygeal	Relating to coccyx
Epigraphy	The study of inscriptions as written history
Epiphyses	Growth plates attached to the end of bones
Intrinsic	Something inherent and natural; an essential part of one's identity
Morphology	The study of form, and how it changes
Munsell	A colour classification system according to hue, lightness and intensity
Necropolis	A cemetery
Osteometry	Study of human and animal skeletons
Relief	A sculpture or carving made on a flat surface (i.e. wall)
Serapeum	A temple or institution dedicated to worship of Serapis (Egyptian deity)
Seriation	Placing of artefacts or objects, of one culture, in chronological order
Spectra	A series of peaks, relating to colour, sound, mineralogy etc, shown according to frequency, charge or energy.
Typology	Classification by type and/or symbols
Victual	Food or provision
Viscera	Internal organs found in the abdominal cavity
Votive	An object given in fulfillment of a religious vow

AD	Anno Domini
AMS	Accelerator mass spectrometry
ANSTO	Australian Nuclear Science and Technology Organisation
BC	Before Christ
BP	Before present
BSE	Backscatter electron image
CBCT	Cone beam computed tomography
CT	Computed tomography
DECT	Dual energy computed tomography
EDS	Energy-dispersive X-ray Spectroscopy
FOV	Field of view
MDCT	Multi detector computed tomography
RGB	'Red Green Blue'
SE	Secondary electron image
SEM	Scanning electron microscopy
XRD	X-ray Diffraction

Abstract

Due to a history of malpractice in archaeology, minimally and non-destructive investigative techniques are necessary to protect precious artefacts and mummified remains for the future. Using a combination of established and novel techniques, X-ray computed tomography (CT) and neutron CT, allowed for non-destructive study of IA.2402, an unusual Egyptian votive mummy of unknown age and provenance. These imaging methods revealed a partial skeleton of a small, juvenile cat. Use of both techniques allows for dual contrast and complementary study of bones, soft tissue, and textile components. Neutron CT, never before applied to archaeometric studies of mummified remains, provided valuable insight into wrapping techniques used in the mummification process. Pigment analysis was performed for coloured markings on the wrappings, using a scanning electron microscope and Raman spectroscopy, to determine their composition and authenticity. Protein extraction and analysis was attempted, however was inconclusive of species due to the decayed state of remains. Radiocarbon dates were acquired, and provided quantitative results to compare with morphological observations and conclusions based on partiality of the contents. All techniques were employed to better define and profile the specimen, within its historical context, while causing as little physical disruption as possible.

1 Introduction

The study of history and its past civilisations, particularly ancient Egypt, can greatly inform the origins of modern traditions and cultures. Through written accounts and epigraphical evidences, the Egyptians illustrated their vast history and culture, allowing 21st century society a glimpse into the past. While these records are invaluable, they predominantly present a historical narrative specially crafted by the nobility and conquerors. Too frequently, this masks how life was truly experienced by the majority: the common citizen, the social minorities, and lower classes. Through archaeology, their perspectives and experiences can be brought to light, and given due consideration.

Historically, archaeological practice has been destructive in nature, both in the field and in laboratory contexts. Unfortunately, this has resulted in irreversible damage to ancient artefacts and mummified remains, and the permanent loss of unique cultural artefact. Such deleterious practices have illuminated the necessity for minimally and non-destructive investigative techniques that maintain the physical state of these unique treasures.

The current social climate of enhanced cultural respect, and recent technological advancements, offers a prime opportunity to promote non-destructive investigative techniques. Novel techniques present an innovative approach to studying the past, allowing for respect and improved cognisance of culture and practice in ancient societies. Demonstrating the capacity of non-invasive and non-destructive techniques may persuade collection curators to allow access to objects and samples. This would help to combat the hesitancy shown towards these novel approaches, and potentially enrich understanding of the mummified remains. The advancement of technology and open-mindedness of the archaeological community will enable future generations to study more facets of ancient Egypt, and the relatively undocumented procedure involved in mummification.

This thesis employs various minimally and non-destructive methods to examine an ancient Egyptian mummified animal of unknown provenance and age. The practice of mummifying animals was an industrial scale enterprise (Nicholson *et al.*, 2015), which produced an enormous quantity of mummified birds, fish, cats, dogs and other animals. The external appearance of an artefact may reveal much about its' socio-political and religious context, and potentially its age. These factors cannot, however, be conclusively identified by traditional means without unwrapping and dismantling the sample. There is no physical way to discern the nature of mummified contents within the wrappings (Brier, 2001; Malgora *et al.*, 2011; Cornelius *et al.*, 2012;). The mummified specimen under investigation (IA.2402) appears to be a cat, due to its markings and wrappings. It is this hypothesis that will be addressed by non-destructive imaging techniques and osteometry.

1.1 Literature Review

1.1.1 *Egyptian religion and animal mummification*

Ancient Egyptian society was deeply religious. They formed an iconic cultural identity, which was tailored and shaped over many millennia by daily piety, deity worship and the concept of the afterlife. Under the protection of the sun god, Re, everyday life involved maintaining the natural balance (maat) and living in harmony with the natural world. No creature was superior to another, rather animals were closely linked with the gods and often stood as representatives of various deities. Evidence of this cultural practice has been depicted in many forms – papyri, wall art and sculptures of human bodies featuring the head of an animal such as a jackal, cat, or hawk. This research thesis focused on cats in Egyptian society and religious practice, due to the abundance of mummified specimens (Zivie and Lichtenberg, 2015).

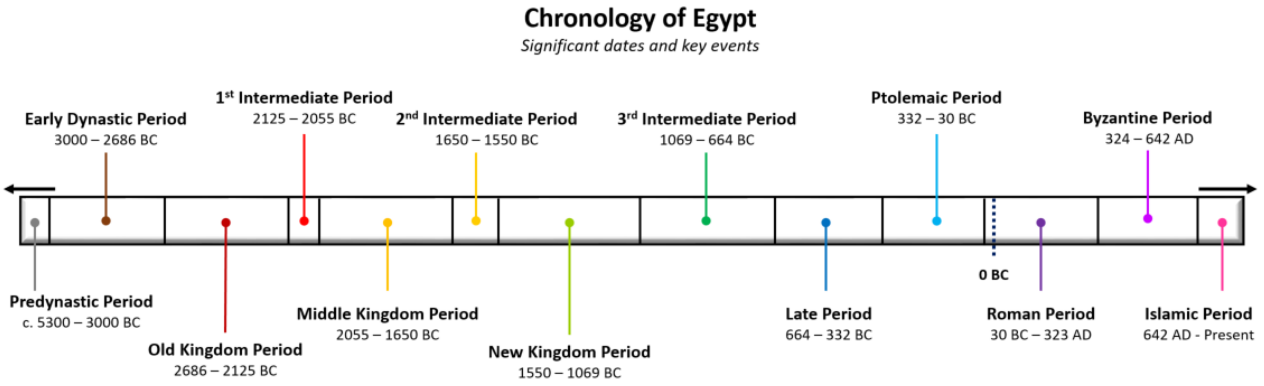


Figure 1. Timeline of ancient Egypt. Dates based on chronology from Shaw (2000).

As early as the Predynastic period (Figure 1 for context) (Kurushima *et al.*, 2012; Van Neer *et al.*, 2014), cats were an integral part of Egyptian society, protecting food reserves from rodents and snakes, and roaming the desert and Nile Delta areas. The goddess Bastet was represented by a cat (originally a Lioness, until the 22nd Dynasty), and she symbolised protection, beauty, fertility and sexuality (Linseele, Van Neer and Hendrickx, 2007; Remler, 2010; Kurushima *et al.*, 2012; Bleiberg, *et al.*, 2013). It could be suggested that the increased interest and focus on Bastet in art and culture was influenced by the late period rulers who came from Bubastis, the location in the eastern Nile Delta region of a dedicated cat cemetery (Ejsmond and Przewlocki, 2014). Appearing in various reliefs on the walls of temple and tombs, as well as statues and amulets, Bastet was represented as a small cat (Figure

Figure 2. Ptolemaic period bronze Bastet statue (Met Museum, Collection: 10.130.1332)

2), often sitting beneath a ladies' chair (Figure 3) (Bleiberg *et al.* 2013); or as a woman with a cat head (Figure 4) (Zivie and Lichtenberg, 2015). Bastet was worshiped in the temple at Bubastis, and honoured at the necropolis at Saqqara, a burial ground for thousands of mummified cat remains (Ejsmond and Przewlocki, 2014; Zivie and Lichtenberg, 2015).

Figure 3. Cat under the masters chair, wall painting from Private Tomb 52 at Nakht, Thebes (Ottoni *et al.*, 2017). Stripy markings appears to be like Felis silvestris species.

It is thought that the Egyptians began domesticating cats during the Predynastic period (Van Neer, Linseele and Friedman, 2004; Linseele, Van Neer and Hendrickx, 2007), as evidenced by a depiction of a cat wearing what could be a collar in a 5th Dynasty tomb at Saqqara (Linseele *et al.* 2007). This is usually a symbol associated with a modern domestic pet, and could be similarly interpreted as a symbol for domestication of an animal. Further examples for cat domestication in Egypt have been found in excavations of burial grounds at Hierakonpolis and Mostagedda, dating to Naqada IC-IIB (c. 3600 BC), in the form of fractured, yet partially healed bones (Van Neer *et al.*, 2014). The state of these bones suggests that the animals had time to heal in a protected environment, as without such, the injuries sustained would probably have been fatal. These discoveries lead to the suggestion that perhaps the feline was first domesticated in Egypt, in the Early Dynastic Period (3050-2663 BC) (Kurushima *et al.*, 2012) reaching completion, at latest, by the Middle Kingdom period (c.1950 BC) (Linseele, Van Neer and Hendrickx, 2007, 2008; Van Neer *et al.*, 2014).

It seems that the Persians in the Levant were also domesticating cats circa 2000 BC, according to a recent study involving carbon dates collected from felines in that region (Ottoni *et al.*, 2017). Regardless of which ethnic group initiated the practice, the involvement of Egyptians cannot be denied, as there were structures specifically assigned to breeding and raising cats in the thousands, to later be killed for mummification (Armitage & Clutton-Brock 1981; Hartley *et al.* 2011; Petaros *et al.* 2015; Plessis *et al.* 2015).

Figure 4. Stelae of goddess Bastet represented as a woman with a cat head, from Mendes, Egypt (Pelizaeus Museum no. 1895)

It is well known that the Egyptians mummified their dead, yet it is perhaps less known that they also mummified animals en masse. The mummification of animals began in the Old Kingdom Period (2649-2150 BC) and continued on to the beginning of the Islamic Period (642 AD) (Harrell & Lewan, 2002; Maurer *et al.*

2002), with changes in wrapping design and style according to the period. There are several types of animal mummification seen throughout this time, mostly categorised according to purpose, either religious or personal. The primary example seen was the mummification of pets, a rare practice reserved predominantly for royalty or elite persons, as it would have been very expensive (Ikram, 2011). Animals were believed equally worthy of the afterlife, and were on occasion buried nearby to their owners' or in their own coffin (Malgora *et al.*, 2011; Cornelius *et al.*, 2012). Examples of this were the pet cat "Tamyt" of Prince Djhutmose, who was mummified and placed in a special limestone coffin (Malgora *et al.*, 2011); or the pet gazelle of Isetemkheb D, which was mummified in the same way as elite humans, with viscera mummified separately and re-placed within the body, before being placed in a large wooden sarcophagus (Ikram, 2005). There are cases where pets of non-elite citizens have been mummified, however it is uncommon (Ikram, 2005; Malgora *et al.*, 2011; Cornelius *et al.*, 2012). Victual or "meat mummies", often dehydrated poultry and beef, were made as food offerings for the spirit of the deceased in the afterlife (*ka*). To date, no cases of feline victual mummies have been recorded (Ejsmond and Przewlocki, 2014). These victual mummies were quite common in the 18th-21st Dynasties (Ikram 2009; Clark *et al.* 2013), with the example of Tutankhamun, who was buried with 25 victual mummies (Ikram, 2005; Cornelius *et al.*, 2012).

Animal mummies were mostly made for religious purposes, and are divided into two subtypes – sacred animals and votive offerings. Sacred animals were worshipped as the incarnation of the god, possessing oracular powers and could communicate with the gods (Nicholson, Ikram and Mills, 2015). Due to this holy status, sacred animals were given elaborate burials, with decorative wrapping and sarcophagi, such as that of the Apis Bull at the Serapeum in North Saqqara (Dodson, 2005; Ikram, 2011; Bleiberg, Barbash and Bruno, 2013). Votive offerings represent the overwhelming majority of animal mummies, serving as a gift to a particular god or goddess, in exchange for a particular blessing one sought such as health, protection or prosperity (Bleiberg, Barbash and Bruno, 2013; Plessis *et al.*, 2015). Votive offerings would have been purchased by pilgrims and lower class Egyptian citizens, and were dedicated at a temple, in exchange for the favour of the gods, or to request something particular from them (Nicholson, Ikram and Mills, 2015; Wasef *et al.*, 2015).

In order to facilitate the vast quantities of votive mummies wanted by the populous, cat breeding grounds appear to have raised kittens to between either 2-4 months or 9-12 months, according to periods of demand for votives before they were killed and mummified (Armitage & Clutton-Brock, 1981; Malek, 1993; Ejsmond & Przewlocki, 2014; Zivie & Lichtenberg, 2015). There were several cemeteries that were dedicated resting places for mummified cats, namely Bubastis, Tanis, Mostagedda, Hierakonpolis, Saqqara, Abydos and Speos Artemidos near Beni

Figure 5. Variety of styles cat mummies, throughout different periods.

a) *37.1991Ea-c Third Intermediate period, Unprovenanced (760 – 390 BC);* ***b)*** *37.1988E Third Intermediate period (750 – 400 BC), Unprovenanced;* ***c)*** *X1179.3 Late Period (664 – 308 BC) Unprovenanced;* ***d)*** *05.307 Graeco-Roman Period, Unprovenanced (305 BC – 395 AD);* ***e)*** *EA37348 Roman period, Abydos;* ***f)*** *EA6753 Roman* period *(post 30BC), Thebes.* (Images from Brooklyn Museum, Manchester Museum and British Museum collections).

Hassan (Malek, 1993; Ejsmond and Przewlocki, 2014). From these sites, examples of votive offerings have been found, in great number and variety according to time period (Figure 5).

Mummification has always fascinated Egyptologists, archaeologists, and amateur enthusiasts alike, for it is mysterious, elusive and appears to hold some esoteric insight into the afterlife that the ancient Egyptians were privy to. The style of mummification clearly changed over time, however the process is not well documented, neither in written, nor epigraphical form. However there are only a small collection of illustrations in Egyptian art that depict aspects of the mummification procedure, i.e. tomb paintings near Thebes and Giza reveal small details of ceremonial wrapping, spells and rituals performed during mummification (Theban Tombs of Thay: TT23 and TT41 (Ikram, 2011)). Later records from historians Herodotus (5th century BC), and Porphyry (3rd century AD), discuss mummification processes, providing the most comprehensive and detailed contemporary account. Consequently, the process for animal mummification has not been well understood until more recently, as a result of destructive techniques.

The Egyptians did not refer to the practice of mummification by this term, rather by the word *Cha-t* or *Shaat* in Coptic (Gliddon, 2008); the term mummification developed later, following the Arabic conquest of Egypt circa 5th century AD. In the process of sealing the body and securing the bandages, substances such as resins, gums, proteinaceous binders and waxes were employed, for example: coniferous and cedar oils, fir and pine resins, mastic, myrrh, beeswax, cassia, juniper and bitumen (Ikram, 2005; Abdel-Maksoud and El-Amin, 2011).

The Egyptians were resourceful in creating paint in various colours from the natural minerals around them, creating their own pigments from circa 4000 BC (Barnett, Miller and Pearce, 2006). The first pigments were derived from natural charcoal and ochre (yellow and red), later joined by malachite (green), lapis lazuli and azurite (blue). These naturally occurring pigments were crushed into powder for mixing with a binding agent such as tempera (egg white) or beeswax (Barnett, Miller and Pearce, 2006). Other minerals such as gypsum (white), jasper (yellow), emerald (green) and turquoise (teal) were also used for creating pigments (Baines, 1985; Ragai, 1986). Each colour symbolised a particular aspect of the Egyptian religious belief, and as a result, each artefact, painting and painted mummy was imbued with deeper meaning according to the colours used.

Many of the resins tend to appear similar to one another after thousands of years, and applied paints often fade or change tone. As a result, various scientific techniques have been recruited to help determine the composition of mummy resins and paints. Raman spectroscopy has been widely applicable to both mineral and organic compounds, compiling online databases with individual spectra and supporting published research (Burgio and Clark, 2000; David *et al.*, 2001; Clark, 2002; Smith and Clark, 2004; Chaplin, Clark and Scott, 2006). This is invaluable in the identification of unknown pigments or resins, as it does not require damage to the artefact, and only needs to use small samples sizes; a primary concern when studying unique mummified specimens. Different types of resins, pigments and binders were used over many hundreds of years, which can be indicative of the time period in which the mummy was made (Edwards and Ali, 2011; Clark, Ikram and Evershed, 2013; Cavaleri *et al.*, 2017).


Figure 6. 'Hawk' mummy scanned using X-ray imaging, reveals an ibis skeleton in the wrapping (Brier, 2001).

Cat mummification reached a peak in popularity between the Late Period (525-332 BC) and the end of the Roman Period (30 BC-395 AD), with increased demands for votive offerings. In an attempt to meet this increased demand, the quality diminished, as did the completeness of the skeletal remains. The occurrence of partial and 'fake' mummies became very common. Many of these 'partial mummy' cases included odd combinations of a head, a limb, or tail; some contained multiple animal skeletons or even the skeleton of an entirely different animal to that represented in the wrapping (Figure 6). In one case of a 'fake' mummy, the wrappings did not contain bones of any kind, rather they were stuffed with plant matter and mud (Brier, 2001; Malgora *et al.*, 2011; Bleiberg, Barbash and Bruno, 2013).

This did not appear to be a concern for pilgrims or Egyptians purchasing votive offerings, as the offerings were never intended to be unwrapped. This raises questions concerning the sanctity of the object, when it is not an entire animal. Ikram (2009) suggests that perhaps the priests considered a 'fake' equivalent to a real mummy if the correct rituals and prayers were uttered in the process of mummification. Alternatively, perhaps the embalmers were using anything they could find that could be associated with an animal throughout its lifetime – eggshell, nest material, a stray bone or fur (Ikram and McKnight, 2015). This would suggest that the notion itself was more important than the actual contents. The only reason that these partial or 'fake' mummies were discovered is due to either destructive investigation or the use of modern imaging methods.

1.1.2 *Destructive vs non-invasive investigation*

As previously discussed, there is little written evidence remaining to provide insight into the practice of mummification. This restricts our understanding of how the embalming and wrapping was performed. Much of what is known about the wrapping techniques has been discerned by destructive investigation, thought to be educational but in reality, tremendously disrespectful to ancient Egyptian culture and beliefs. In 18th century Victorian Britain, Egypt was a heavily romanticised phenomena, labelled Egyptomania (Shaw, 2004). This heightened interest encouraged looting and removal of priceless artefacts as souvenirs, as it was "hardly respectable" for one to return home from Egypt without "a mummy in hand" (Ikram and Dodson, 1988; Smith, 2016). At this time, mummy unwrapping parties became popular within affluent society, not so much for the research or educational value as for entertainment and curiosity (A. David, 1997; S. T. Smith, 2016). Many mummies were damaged or destroyed entirely by such ignorant practices, however destruction also occurred during scientific investigations, which intended to provide insight into the wrapping techniques and patterns. Margaret Murray was one such scientist to unwrap two human mummies and record her discoveries in detail, with the aid of an interdisciplinary team in 1908. By unwrapping mummified cats retrieved from the Bubasteion (cat cemetery at Bubastis), much has been discovered about the variety of cat species, number of layers of textile, tightness and corkscrew style of internal wrapping, and average length of the bandages (Ginsburg, 1999). Such practices were understandable for these archaeologists, given unwrapping was the only way to learn of the process at the time, but now that there are so many non-destructive options available, this kind of study is no longer acceptable.

Two main species of cat were mainly found in Egyptian mummies (Appendix 1). The first is *Felis silvestris libyca*, known as the "sand cat" or "African wild cat", which came from the desert and Nile River regions (Armitage and Clutton-Brock, 1981; Malgora *et al.*, 2011; Kurushima *et al.*, 2012). It had a small frame, with light sandy-brown fur and a long tail (Armitage and Clutton-Brock, 1981). The other is *Felis chaus*, known as the "jungle cat" or "swamp cat", as they dwelled mostly in the Delta and Nile Valley area (Malek, 1993). This subspecies of cat was much bigger than the *Felis silvestris,* with a long skull, yellow-red fur, and a short tail (Armitage and Clutton-Brock, 1981). There is one unusual case reported of a particularly large mummified cat, but the majority of mummified cats that have been studied in detail are either of the *Felis silvestris* or *Felis chaus* species (Ejsmond and Przewlocki, 2014; Johansson *et al.* 2015). The large majority of mummified cat remains studied to date have been identified as *Felis silvestris,* suggesting that these were being domesticated in Egypt.

1.1.3 *Paleoradiology and Archaeology*

The discovery of X-rays and the associated invention of X-ray radiography in 1895 by physicist Wilhelm Röntgen (Janssens and Van Grieken, 2004) has had a positive impact on the study of precious mummified animal remains, as it has allowed for non-destructive and non-invasive investigation. The first documented experiment using X-ray radiography on Egyptian mummified remains was in 1896, by Konïg and Thurston Holland (David, 1997), who obtained a transmission image of a mummified child, a cat and a bird. X-rays pass through fabric wrapping with ease and effectively image denser objects inside: bones, rocks or metallic artefacts. This is because denser materials like bone and metals absorb more photons, and thus appear more opaque in X-ray radiographs than do soft tissue and organs (van der Plaats and Vilibrief, 2012).

X-ray use for imaging was limited at first, as they were only able to produce two-dimensional radiographs of objects according to density and thickness of materials. With further development and refinement of computational techniques, as well as computers in general, there was increased ability to form 3D virtual reconstructions. The men credited to inventing computed tomography, Allan Cormack and Godfrey Hounsfield, were awarded the Nobel Prize for Physiology or Medicine in 1979 (Cierniak, 2011). Both went on, individually, to solve theoretical issues with reconstructing the X-ray projections, and Hounsfield eventually constructed and patented the first CT-scanner in 1968 (Cierniak, 2011).

In 1972, computed tomography (CT) was introduced to the scientific community, and in late 1973 the first commercial CT scanner, the EMI CT 1000 became available (Cierniak, 2011). X-ray CT was first utilised in mummy investigations in 1979, by Canadian (Harwood-Nash, 1979) and British scientists (Isherwood, Jarvis and Fawcitt, 1979). The Manchester Mummy project has been instrumental in imaging 280 mummified animals over 12 years (2000-2012) using radiology facilities at the various hospitals across the city (Adams, 2015). In addition, other imaging studies have been undertaken since 2000, however many of those involving cat mummies have been more recent (2011-present). The Trento cat mummy investigation (2011) utilised X-ray CT to verify the contents and authenticity of the mummy, and was successful in revealing a virtually complete skeleton, aside from a few missing vertebrae in the spine (Malgora *et al.*, 2011). In 2014, the National Museum in Warsaw undertook CT studies on five cat mummies in their collection, to better understand what was encased in the wrappings. The results showed that three of the five were relatively intact, and that the entire wrapping was sometimes bigger than the encased animal (Ejsmond and Przewlocki, 2014). The CT results most effectively showed the position of the skeletons in the wrapping, which were similar to that of the Trento case study. The stance of the animal appears like it is “resting on its haunches”, with its front legs either drawn up to the abdomen, or sitting along its sides. Often, the tail of the cat is often tucked up between the hind legs and around the torso. This posed stance has become recognisable across many cat mummies (Figure 7); it has been an informative outcome of these CT studies (Mcknight, 2015), revealing a technique employed by embalmers to form the typical cylindrical shape of the cat mummy.

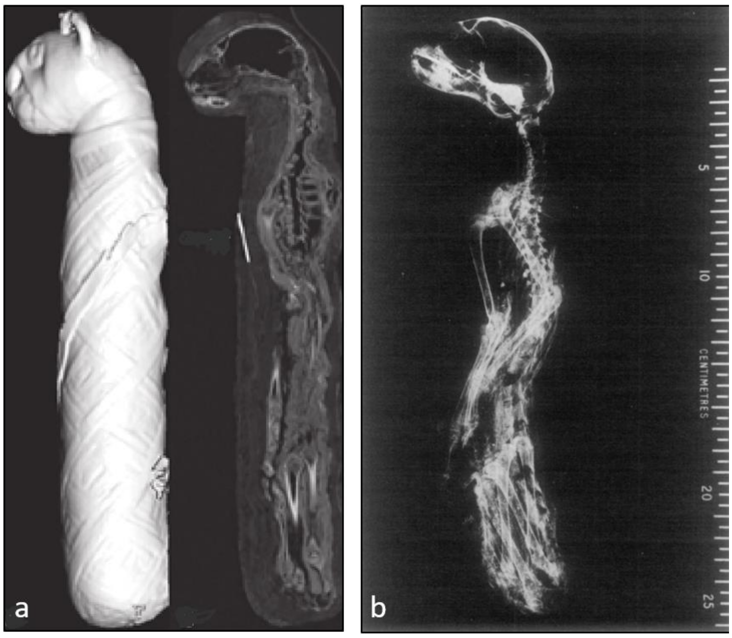


Figure 7. X-ray CT data of various cat mummies, showing trend in position of mummy in wrapping – sitting on hind legs. ***a)*** (Malgora *et al.*, 2011); ***b)*** (Armitage and Clutton-Brock, 1981).

X-ray CT scans have also revealed potential causes of death in some cases, showing breaks or significant injury to the skeleton of the animals. Fractured bones, depending on the type of fracture, can be attributed to either perimortem or post-mortem forces, inflicted intentionally or as a result of the mummification process (Petaros *et al.*, 2015; Bewes *et al.*, 2016). The example in Figure 8 shows how X-ray CT can be


Figure 8. X-ray CT data showing broken femurs (Petaros *et al.*, 2015).

informative to cause of death. The fractured bones could be the result of perimortem inflicted injury, however in this case, it is more likely caused by post-mortem manipulation of the body, especially if rigor mortis had occurred (Petaros *et al.*, 2015). It is not always clear if the injury was the cause of death, but some injuries such as an oblique fracture trauma to the skull or a broken neck could be determined as fatal (Malgora *et al.*, 2011). Even though it can be difficult to determine if a fracture or break has been cause of death, Bewes *et al.* (2016) mentions some ways to identify post-mortem breaks, i.e. transverse fractures through the cervical spine with break extending into surrounding desiccated tissue. Obviously, such assumptions can only be made if the skeleton is complete, as having an incomplete or partial skeleton makes determining cause of death ambiguous and speculative.

1.1.4 *Neutron Tomography: a novel approach*

Neutron tomography is a relatively novel imaging technique when compared to X-ray and medical resonance imaging (MRI) in archaeological investigations. It is a 3D imaging technique that uses neutron attenuation to reveal the internal structures or contents of an object. The interactions of X-rays with matter involves the electron cloud that surrounds the nucleus of an atom, while neutrons interact with the nucleus itself, making them fundamentally different. X-rays are attenuated more by dense materials, or those composed of higher atomic mass elements. Like X-rays, neutrons are attenuated more by dense materials, however their attenuation is not correlated with atomic mass; in fact, some light elements such as hydrogen and boron have very high thermal neutron attenuation coefficients.

Neutrons were first discovered by James Chadwick in 1932, and neutron radiography was developed by Kallman and Peter in the late 1930s (Nguyen, 2011). Neutron radiography offers complementary information to X-ray radiography, particularly where density, object size, or the presence of metals prevents structural study with X-rays. Traditionally neutron CT is used in the examination of pigments in artworks, and metallic structures for faults or defects, i.e. ball bearings or engine parts, the mapping of water distribution in fuel cells, and the investigation of carbon fibre composites, where X-rays simply do not yield contrast (Prudencio *et al.*, 2013). The application of neutron CT more recently spans from the digital and virtual excavation of fossils from rocks (Mays *et al.*, 2017), through the structural integrity of 3D printed aerospace composites, to the moisture uptake of plant roots (Fritzsche, Huot and Fruchart, 2016).

To date, there are no published accounts demonstrating the application of neutron radiography or CT to wrapped mummified remains, there is one case of neutron tomography performed on an unwrapped mummified child’s head (Salvemini *et al.*, 2016). Consequently, this relatively novel technique is surrounded by a number of concerns. The first is that neutron CT requires access to a neutron source, and these are both limited in number and can be difficult to access. According to the International Society of Neutron Radiology, there are only 13 operational neutron CT instruments worldwide, and an additional three that are built but not currently available (Bücherl, 2017). As this is a nuclear method, it requires the sample to be irradiated with particles for a short period of time. The ionising dose to which samples are exposed is not well known, nor documented to date, thus their impacts on cellular degradation of ancient biological material are unknown. Furthermore, neutron irradiation results in neutron activation and temporary residual radioactivity of the object. Depending on the energy and intensity of the neutrons used, and composition of the samples studied, the artefact may remain radioactive for periods of time between hours and years (Bettuzzi *et al.*, 2015) (J. Bevitt, personal communication, 16 October 2017). High resolution neutron CT scans typically take several hours to days, depending on sample size, to collect a full 360° (Lehmann, Hartmann and Speidel, 2010; Prudencio *et al.*, 2013), compared to the seconds to hours that are involved for similar X-ray CT scans. Despite these factors, neutron CT has the potential to greatly contribute to non-invasive and non-destructive imaging studies, as it offers a complementary set of data to that of X-ray, yielding a more comprehensive view of the sample.

An excellent illustrative example of a combined X-ray and neutron CT study was undertaken in 2010 on a small selection of bronze Buddhas from Tibet; the statuettes were scanned using both imaging techniques, yielding useful and complementary data (see Figure 9). While the X-ray struggled to penetrate the thick metal, it provided information about the thickness in various areas across the sample. The neutron results showed that each Buddha had a combination of organic contents such as seeds, a ‘soul pole’ or *tsog-sin*, a silk scroll containing religious texts, and wire (Lehmann, Hartmann and Speidel, 2010). Additionally, traces of ceramic residue were found

Figure 9. ***a)*** X-ray radiograph of Buddha statue. ***b)*** Photograph of Buddha statue. ***c)*** Neutron tomograph of Buddha statue (Lehmann, Hartmann and Speidel, 2010).

inside the cavity, which suggest a manufacturing technique that was used in the 14th-15th centuries in Tibet. This information confirmed that the sample was authentic in origin and date (Lehmann, Hartmann and Speidel, 2010).

Both techniques have the capacity to non-invasively study these objects. This allows protection of their intrinsic and religious value, while permitting a validation of their authenticity, which is important to the ethnic group to which the artefacts pertain. The application of these techniques to mummified remains would permit investigation of the textile layers, and the process in which the mummy was wrapped. Additionally, neutrons may provide more information about any soft tissue or hydrogenous materials within the wrapping, without physically unwrapping or destroying the sample. In acknowledgement of the gaps in the literature and available information regarding mummification and votive offerings, the key aims of this study are to address the age, authenticity and contents of the mummified specimen.

1.2 Research aims

This study will address the issue of authentic and counterfeit votive mummies in a spectrum of 70 million known Egyptian animal mummies, by non-destructive imaging techniques, both established and novel in archaeometry. This thesis aims to combat hesitancy toward novel scientific techniques, in imaging the mummy at a neutron CT facility, in order to compare and contrast neutron CT versus X-ray CT. There are no spallation neutron sources in Australia and only one nuclear research reactor, called the Open Pool Australian Lightwater (OPAL) reactor. This is located at the Australian Nuclear Science and Technology Organisation (ANSTO), in Lucas Heights, NSW. OPAL provides a neutron source to the DINGO neutron imaging and radiography instrument, licenced for international research since November 2014 (ANSTO, 2014). This would help to determine their complementarity toward the study of mummified remains. While X-ray CT instrumentation is commonly accessible within university laboratories, and hospitals, access to neutron CT instruments is extremely limited. Neutron CT instruments utilise neutrons, subatomic particles that are unstable and have a limited lifetime. High-intensity neutron sources, and thus neutron CT instruments, are only available at nuclear reactor or spallation neutron source research facilities. Access to these nuclear research facilities is highly competitive and primarily based on a peer-reviewed merit process.

A significant aim in this thesis was to write a research proposal/grant to achieve access to a neutron imaging instrument through a peer-reviewed merit process so that the mummified specimen IA.2402 may be investigated in this manner. There is no record in the literature of the application of neutron imaging to mummified Egyptian remains. Achieving access to a nuclear reactor-based neutron CT instrument during this thesis is therefore a significant potential achievement in this field, and paves the way for similar research to be conducted by others in the field

A comparative study using neutron and X-ray CT will allow for investigation of the internal features of the specimen without altering it in any way, and will potentially provide answers to many questions that surround these remains:

1) *What is inside the wrappings?* Using a combination of neutron and X-ray CT, previously unknown information about the animal (age, species etc.) and mummification techniques will become available. These methods will provide a comparative study of imaging techniques, and demonstrate how using a combination of methods can provide a more complete picture of the mummified specimen (Brier, 2001; Kretschmer *et al.*, 2004; Mannes *et al.*, 2015). Having new information about the contents of the wrappings will also potentially inform about socio-political and religious context in which the mummy was produced enabling a glimpse into the life of the common people in ancient Egypt.

2) *What can be gleaned from examination of the wrappings?* Examining the internal wrappings, using neutron and X-ray imaging techniques will illuminate information about the mummification process: how it was performed, what materials were used, and how many layers of textile. Using X-ray CT information about the materials used and contents of the wrappings will potentially be revealed. There is interest to see how neutron CT compares to X-ray CT.

3) *Is this an authentic mummy or a 'fake'?* A lack of context raises many questions regarding provenance, age, and ultimately authenticity of remains, as genuine ancient artefacts, ancient fakes or modern fakes are hard to distinguish from one another. It is important therefore to determine the authenticity of the specimen by using non-destructive imaging and radiocarbon dating. A major factor will be to confirm if there are indeed remains encased in the wrappings. Radiocarbon dating will enable dating of the external wrapping, and verify if they are the same age as the remains. If they do not correlate, it could suggest that the sample is a 'fake', has been interfered with at some point, or that the contents have been recycled in ancient times

4) *Can the external markings indicate the context of the remains?* Investigation into the coloured pigments used on the wrapping will help to better understand materials used in the mummification process. Raman spectroscopy, Scanning Electron Microscopy

(SEM), and X-ray Diffraction (XRD) were applied in an attempt to determine the composition of the paints, and the authenticity of the specimen. Of particular interest is if the markings can be determined as original or modern additions.

5) *How old is the mummy? How can a date be determined for the remains?* Very little is known about the origin of this sample, including how old it is. Knowing the age of the remains is important for placing it as precisely as possible in the correct historical context. Therefore, radiocarbon dates were acquired. These dates will be compared with relative dating techniques such as morphology, seriation, and typology, to attempt to place the remains in their correct context.

With the above sections considered, the main aim of this thesis is to use non-destructive techniques, X-ray CT and neutron CT, and other auxiliary techniques to investigate the authenticity and provenance of the mummified specimen presented here. This aim can be broken down as follows:

1. The mummified sample will be visually described and examined for key features that may link it to a time period or place.
2. Age dating will be carried out in an attempt to determine the authenticity of the specimen and place it accurately in a particular period or Dynasty of Egypt's chronology.
3. The mummified specimen will be imaged using X-Ray CT and Neutron tomography techniques in an attempt to determine what is within the wrappings, wrapping techniques used, and if this matches the exterior appearance.
4. Wrapping style as well as binder and pigment analysis, via Scanning Electron Microscope (SEM), Raman spectroscopy and X-ray Diffraction (XRD) will be carried out with the aim of determining geographic and socio-economic context.

2 Description of IA. 2402 Mummified Specimen

2.1 Appearance

The specimen was observed and described on the 30th of March 2017, by Dr Joseph Bevitt, and Miss Carla Raymond, at ANSTO. The outside of the wrapping is in overall good condition, made to appear as a small cat; the general shape is an irregular cylinder, with a bean-like 'body' and small rhomboidal 'head' on top (Figure 10). The specimen, from the tip of the 'ears' to the extant base, measures 21.29 cm (marked in green on Figure 10b). The 'ears' are bending inwards and were not extended to full height for more accurate measurement due to their fragile condition. Across the broadest section of the specimen, the width measures 4.79 cm, and the depth, 7.82 cm (red on Figure 10b).

Figure 10. Egyptian mummified specimen. a) left side; b) right side. Red line marks breadth, green line marks height.

The 'head' of the specimen is quite small, measuring 4.83 cm wide at widest point, 3.8 cm long (crest to start of red neck markings), and 6.59 cm breadth. There is a distinct crest on the top, with two flattened sides that appear to be separate pieces of textile, particularly on the right side (Figure 11a), sloping to meet the 'ears'. The front-most section is also flattened, with a few loose ends of textile to the left side. There are a few areas of fraying textile on the 'head', most likely the result of wear over time. The 'ears' appear to be folded fabric, rather than wrapping around the ears of the animal (Figure 11b). The left ear is 1 cm wide, and 2.97 cm tall, while the right ear is 0.81 cm wide and 3.18 cm tall. The left side of the specimen appears to be in good condition, as most of the textile is still well secured (Figure

Figure 11 ***a)*** Front and ***b)*** back of the 'head'.

10a). The right side is in good-to-poor condition, with a few loose ends of textile near the base of the specimen, and a small worn area just below the band markings (Figure 10b). While the mummified specimen has been protected in the box, the right side has been the reverse, and is rarely seen.

There is a considerable opening in the inferior, where the textile has unravelled and is mildly fraying. The opening does not appear to be the result of wearing, rather it seems like a break or crack has formed (Figure 12). This could be due to rough handling or intentional cutting (Ejsmond and Przewlocki, 2014). The opening in the inferior measures 8mm wide and 21.5 mm long, running from the right posterior to anterior. Through the opening in the inferior the remains can be seen. The remains extend beyond visibility into wrappings, with blackened, dry skin, hair follicles and reddish-yellow to red-brown fur (Figure 13). This colour could be attributed to the kind of resin used during mummification. The small section of exposed skin was the location of fur sample acquisition. The sample of fur acquired from this exposed region was minimal, thus the 'bald' area visible in the photograph is a result of environmental exposure and abrasive wear. The fur sample (Figure 13) is coarse and straight, with an average length of 5-10 mm.

Figure 12. Hole in inferior of specimen (lower left side). Small area of the encased animal can be seen through the broken textile.

Figure 13. Fur sample taken from specimen, through hole in textile (Figure 12). Fur colour varies between Munsell 5yr 7/6 to 7.5yr 7/8, 5yr 3/4, and 2.5yr 2.5/2.

2.1.1 *Markings*

There are painted decorations on the textile that cover the body of the specimen from top to bottom (Figure 14). On the 'head' of the specimen there are two red circles with black dots in the centre. These are situated on either side of the 'head' (Figure 11a), on the sloping sections from the crest. On the flattened section at the front of the 'head' there is a slightly concave red line, running horizontally. Each 'ear' of the specimen has been painted green on the exterior face and red on the interior face. The red, green and black coloured markings have been added after the brown substance (Figure 11). Around the narrow section between the 'head' and 'body' are two coloured bands, one green and one red. These bands also have lines drawn perpendicular to them in a downward direction. It appears the brown was applied first, followed by the green, then red, as red overlaps areas of green pigment.

The painted features on the rest of the specimen are depicted in both green and red pigments (Figure 10). The first set of markings (from the top) are chevron shaped, pointing downwards. The lower markings are also chevron shaped, however point upwards. It appears that red paint has been applied after green, as can be seen in areas where the red paint overlays the green paint. On the right side, by the lower green markings, two irregular red-brown marks overlay the green pigment. It does not appear to be the same substance as the brown resin.

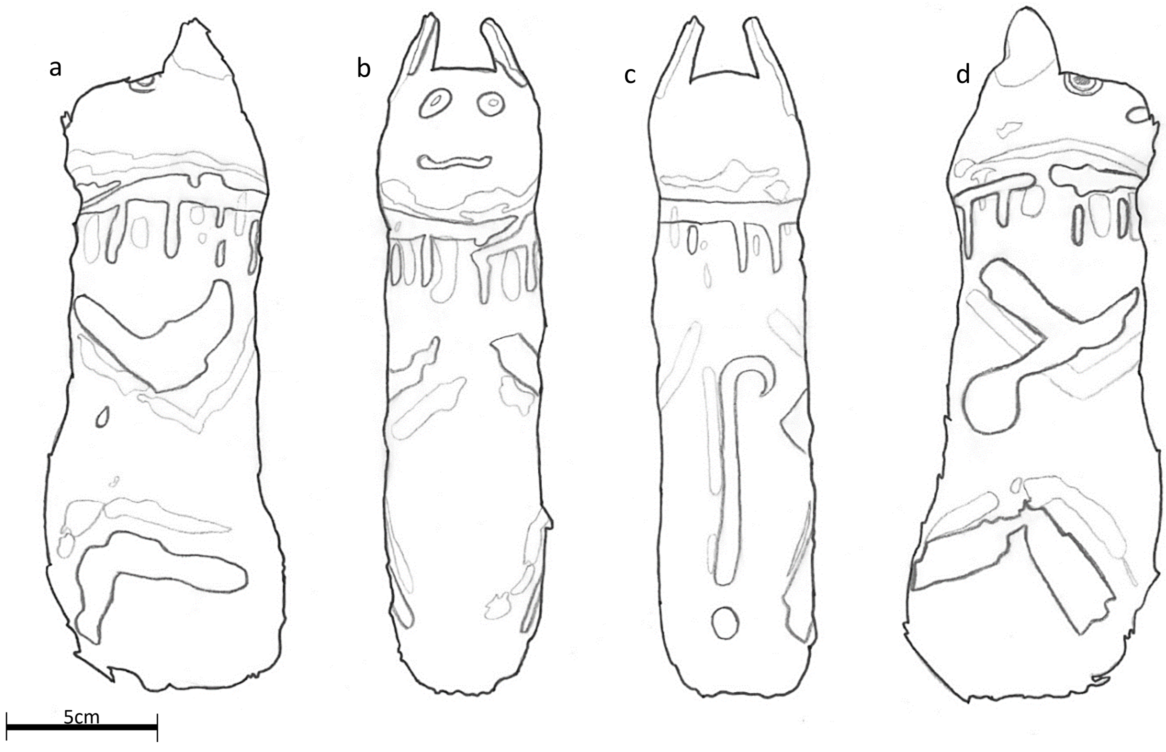


Figure 14. Sketches of mummified cat markings. a) Right lateral; b) Anterior; c) Posterior; d) Left lateral. Bolder lines mark red pigment, and thinner lines mark green pigment. Sketch by C. Raymond.

As previously noted, a brown substance can be seen on the outer-most wrapping. It appears to be acting as a glue to stick the fabric together, particularly in areas where the fabric ends (Figure 15) It does not appear to have been applied in any detailed pattern or style, in contrast to the green and red markings, but is rather random in nature. The brown paint does not cover the entire object, leaving areas of un-coloured textile across the specimen.

On the posterior of the specimen, there are more markings, in red and green pigments. In red, there is a long straight line marked which curls over to the right at the midpoint of the back. Beside the red is a straight green line also; however this one does not curl over to the right. Below these lines is a single red spot (Figure 16).

Figure 15. Brown substance over raw edges of wrappings.

Figure 16. Markings on posterior of mummified specimen.

2.1.2 *Wrappings*

The bandages wind down, in a corkscrew pattern, from the narrow section below the 'head' towards the base. Then the end of the bandage is wrapped around the bottom of the specimen, coming back up on an angle and secured with the brown substance (Figure 15). There are no patches, or signs of stitching or mending present on the specimen. The textile itself is a plain, coarse weave without selvedges (Figure 17). The weave is loose, with S-spun individual threads (Figure 18), some more tightly wound than others.

Figure 17. Weave of textile under magnification (threads average ~0.5mm in thickness, with finest measuring 0.3mm and thickest 0.8mm in diameter).

Figure 18. Individual threads exhibiting ‘S’ spin.

2.2 Curatorial History

David Searle, the Curator of the Australian Institute of Archaeology collection in 1970 has confirmed that the mummified cat was in the collection of the Institute by 1969. However, he is not aware of its origin. An inspection of the lists of Egyptian material that came from agents in Cairo in 1938 and 1954, and from Lady Hilda Petrie in 1949 do not list mummified material. In November 1950 James Stewart, the Curator of the Nicholson Museum, arranged for an embalmed head to be transferred to the Institute. The material is listed in the 1870 and 1891 catalogues of the Nicholson collection (Nicholson, Charles Sir Bart, 1891 *Ægyptiaca; comprising a catalogue of Egyptian antiquities ... now deposited in the Museum of Sydney, etc. [Illustrated.]*, London: Harrison & Sons, 15, No 32).

Item No. 30 in the catalogue is a mummified cat. A number of other items in the catalogue now appear to be in the Institute collection although no reference is made to these items in Stewart’s correspondence, which is now held by the Institute. There are a number of objects, such as Vounous pottery and cuneiform tablets, originally held by Mr Beasley that are now in the collection of the Nicholson Museum. It therefore seems likely that the mummified cat was provided to the Institute by the Nicholson Museum. The objects in the 1891 Nicholson Museum catalogue were collected in Egypt by Sir Charles Nicholson in 1856-7 and brought to Australia to form the basis of the Nicholson Museum collection.

2.3 Provenance

The cat mummy was brought to Australia without record of provenance. It can be very difficult to provenance an object when so little is known about it, however there are a few key features that can help with identifying an objects provenance. By examining the style of wrapping, and the painted markings, it is possible that a similar example of mummification may be found and matched. This could indicate where the remains are from.

The hypothesis for this mummy, is that it was made sometime between the Late Period and the Roman Period (Figure 19); this was determined after a detailed observation of the specimen and observations of mummified specimens similar style and features, i.e. ‘Ears’, and corkscrew, downward spiral wrapping pattern (Figure 20). While these samples do not exhibit similar painted markings as the case study (Figure 20e), they have some similarities. It is more likely an earlier example (Late Period), as it does not have ornate weaved wrapping like many of the Roman period specimens. Carbon dating could place the specimen in a more accurate time frame, and elemental analysis on the pigments could hopefully help to identify from which period the specimen pertains, to test this hypothesis.

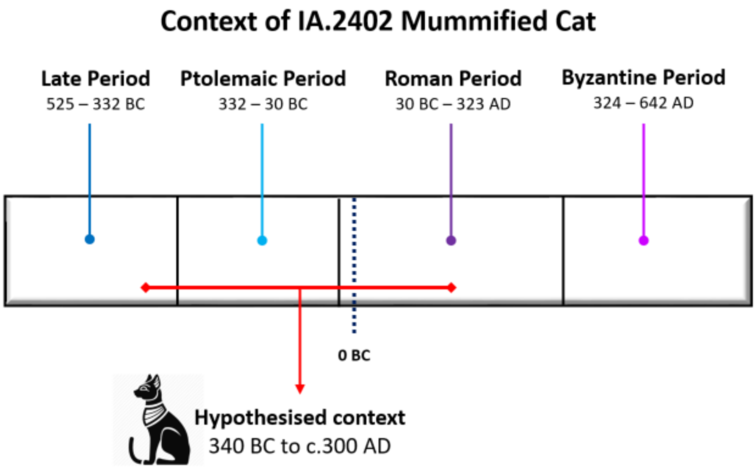


Figure 19. Estimated historical context for mummified specimen IA.2402.

Figure 20. Stylistic features of mummified cats from Late Period context.

a) 05.307 305 BC to 395 AD; ***b)*** NMR.30 525 to 30 BC; ***c)*** 79.3 300 to 200 BC; ***d)*** 79.2 400 to 200 BC; ***e)*** IA.2402 unknown date; ***f)*** X1179.3 664 – 308 BC ; ***g)*** NM84.2 525 BC to c.300 AD; ***h)*** NM62.586 525 BC to c.300 AD.

Hyperlinks connect to museum databases.

3 Methods

3.1 Non-destructive Imaging techniques

3.1.1 *Neutron Computed Tomography*

The mummy was neutron-CT scanned using the DINGO neutron-imaging facility at the Australian Nuclear Science and Technology Organisation (ANSTO), in Sydney, Australia. The sample required no preparation for this process, however it was wrapped in aluminium foil (invisible to neutrons) to position it vertically, and to provide a degree of physical protection on the instrument's sample stage. As the long-term impacts of neutron irradiation on ancient mummified remains is currently unknown, the neutron CT scan parameters were implemented in such a way to minimise the length of exposure of the specimen to neutrons, and this to minimise the potential for radioactivation and cellular ionisation (Table 1). It was determined that conducting a CT scan optimised for high resolution (~25μm pixel size), would require irradiation of the specimen for a period of no less than 3 days. Instead, a low-resolution scan (pixel size of ~9.5μm) was agreed upon to reduce the scan time and exposure to neutrons to a minimum. It is important to note that thermal neutron irradiation over the length of the measurement was calculated to have no measurable impact on the ^{12}C:^{14}C ratio via neutron capture and transmutation, and thus no measurable impact on apparent radiocarbon age.

A total of ten open beam and dark images were collected prior to scanning the mummy, necessary for normalisation of radiographs during the reconstruction process. A series of 720 radiographic projections were captured at set increments of 0.25^{o} over 180^{o} of rotation of the specimen about its vertical axis. The 20x20cm detector was chosen as a compromise to the 30x30cm detector, prioritising higher resolution and sacrificing radiographs including the ears of the specimen (outside FOV). Once collected, the data were processed using the software package Image J (NIH) to create an image sequence, and Octopus 8.2 (Octopus Imaging) software to refine and filter. The data were reconstructed using VG Studio 3.0 (Volume Graphics), allowing for the creation of 3D images and videos of the mummy.

Upon completion of the neutron CT scan, the radioactivity of the specimen was measured as 26μSv/h using a Canberra Radiagem^{TM} 2000 Portable Dose Rate and Survey Meter. After 24hrs the radioactivity of the sample had dropped to 1.5μSv/h, and was not detectable 3 days after the exposure. At this point, a radiological clearance certificate was obtained, providing formal approval for the release of the specimen from the neutron-scattering laboratory, and for the return of the unaltered specimen to the Australian Institute of Archaeology.

DINGO Parameters	
Beam Mode	Parallel Beam
Intensity	Low intensity (L/D=1000)
Detector	^{6}LiF ZnS Scintillator (50μm)
Camera	CCD
Field of View (FOV)	20 x 20 cm
Pixel size	95.5 μm
Capture exposure	23 seconds
Rotation increments	0.25°
No. of Projections	720
No. of Slices	2048
Matrix	2048 x 2048 pixels
Total scan time	11hr 44min

Table 1. DINGO parameters for data acquisition.

3.1.2 *X-ray Computed Tomography*

The mummy was X-ray CT scanned using a Newtom 5G (Newtom, Italy) cone-beam computed tomography (CBCT) scanner, and a GE HD750 (General Electric, Milwaukee, USA) multi-detector (MDCT) and dual-energy (DECT) scanner, located at Macquarie Medical Imaging, at Macquarie University Hospital in Sydney, Australia. All scans were performed by Professor John Magnussen and his team.

The sample was placed on its right lateral side, and propped up on a foam block to provide some protection and to position it more ideally for axial data acquisition. The specimen was then loaded head-first into the scanner, first the Newtom 5G, then the GE HD750. Data acquisition took a matter of minutes per scan, allowing for a total of six scans to be acquired: three CBCT, two MDCT, and one DECT (Table 2). These parameters were set so as to examine the specimen in more detail, utilising the different functions of the scan types. In X-ray CT data acquisition, the voltage applied can be varied according to the radiation absorption edge of the material to be imaged; lower voltages result in the loss of characteristic details or lines, which allows for observation of feature at lower levels of absorption. Tube current is also variable, as it controls the number of electrons that are used to bombard the sample material, and as a result the intensity of the x-ray output. Voxels are defined as 3D pixels, and the size of the voxel directly impacts the sharpness and resolution of the data. The data were analysed using InteleViewer 4-11-1-P130, where various filters (kernels) were applied to better reveal the contents, and reconstructed in 3D using RadiAnt DICOM Viewer 3.4.2.

	CBCT (cone beam)	MDCT (multi detector)		DECT (dual energy)
Scan type	Helical	Helical	Helical	Helical
Voltage	110 kVp	120 kVp	120 kVp	High: 140 kVp
				Low: 80 kVp
Matrix (pixels)	544x544	512x512	512x512	512x512
	1020x1020			
Voxels (X x Y x Z)	0.15x0.15x0.15mm	0.195x0.195x0.615mm	0.195x0.195x0.615mm	0.195x0.195x0.615mm
SFOV	18cm	18cm	32cm	32cm
DFOV	8x8cm	10cm	10cm	10cm
	15x5cm			
Beam coverage	Middle	Whole object	Whole object	Whole object
Slices	548	396	792	301-312
Kernel	8x8cm HiRes	Soft	BonePlus	
	15x5cm HiRes			
Orientation	Axial	Axial	Axial	Axial
	Coronal			
Tube current	1 mA	120 mA	120 mA	640mA

Table 2. X-ray CT parameters for CBCT

3.2 Pigment Analysis

For this investigation, four small samples were carefully removed from the mummified specimen, or from its box. These include a) three threads of yarn removed from the base of the mummy; b) fur extracted from the opening at the base of the mummy; c) wrapping fragment from the box featuring the red pigment; and d) wrapping fragment removed from the mummy featuring green pigment (Figure 21). Samples A) and B) in Figure 21 will be used for radiocarbon dating; samples C) and D) will be used for elemental analysis of the pigments.

Figure 21. Samples taken from animal mummy. (Left to right) Threads removed from worn inferior; Fur and skin fragment from the exposed animal body part in inferior; Red pigment from box (unsure where on sample this has come detached); Green and brown pigments on textile removed from right lateral.

3.2.1 *Sample Preparation for Scanning Electron Microscope*

Two fragments of the mummy's external wrapping were prepared for pigment analysis (c) and d) in Figure 21), one with green pigment and one with red. Each sample was cut into two small rectangles (referred to as *B1* and *C1*) with a sterilised scalpel, and mounted onto double-sided carbon tape on a flat stub. Leftover sample has been kept for future investigation (referred to as *B2* and *C2*). A copper grid was also mounted to the carbon tape for calibrating the instrument prior to data collection. The samples were then carbon coated using an Edwards Auto 306.

3.2.2 *Scanning Electron Microscopy (SEM)*

SEM is a technique that uses a focussed, high-energy electron beam that interacts with the sample, and generate x-rays, as well as secondary, and backscatter electrons (BSE). X-rays are received by an energy-dispersive spectrometry (EDS) detector, which, once calibrated can quantitatively determine the overall chemical composition of the sample to ~0.5 wt%; also allowing for elemental mapping. BSE produce images that show relative elemental distributions where a brighter response is indicative of heavier elements being abundant, relative to the duller or darker responses in the image. Secondary electrons generate images that primarily show the topographic and structural features of the same and are useful in discerning mineral boundaries and structures, and surface textures. SEM is therefore useful to include in this study, as it would allow for a closer, more detailed look at the textile fibres. It would also illustrate the nature of the pigments used on the wrappings, made possible by the high magnifications and high resolutions possible (>10,000x magnification). The high-resolution images allow elemental analysis on a micro-scale, to better understand the composition of the pigments, as well as inform about ancient pigment microstructures.

The sample stud was placed into a ZEISS Evo MA 15 Tungsten SEM, with an Oxford Instruments X-max 20 mm^2 SDD energy-dispersive spectrometer (EDS). The samples were analysed at 20keV and a working distance of 12 mm. EDS was calibrated against a copper mesh grid with response measured to resolve peak shape and intensity of the copper K at a known working distance. Calibrating in this manner ensures that the appropriate working distance from the beam head to the sample is used to guarantee the correct take off angle of the x-rays from the sample surface to the EDS detector, thus increasing analytical precision. Throughout analysis the calibration against the copper grid was checked to resolve drift within the detector over time. Importantly, while this type of calibration will normally yield quantitative results to 0.5%wt., that nature of the samples, uneven and unpolished fibrous organic materials, analysed in this study dictates that at best these analyses can be semi-quantitative study.

3.2.3 *Raman Spectroscopy*

Samples *B2* and *C2* were analysed using a JY Horiba LABRAM HR Evolution confocal laser Raman system. Analysis utilised the (red) 633 nm wavelength laser at 25% of maximum laser intensity. Laser intensity was intentionally reduced to avoid damage to the samples, allowing for multiple analysis' and methods to be undertaken on the specimen samples B2 and C2. The system was calibrated using the 520.7 cm^{-1} silicon peak, before placing one sample at a time on the stage. The 1800 grooves/mm grating was selected for maximum spectral resolution, with slits set at 100 µm, and hole size set at 300 µm. As the pigment to be analysed was unknown, the wavenumber range was set as 200-4000 cm^{-1} for both *B2* and *C2*. Spectra were collected for 10 seconds and averaged over 10 scans. As Raman and SE data were collected concurrently, post-acquisition identification of peaks was undertaken with knowledge of elemental compositions. Therefore, a number of minerals were isolated as highly likely sources of the pigments used. These minerals are outlined below.

3.2.4 *X-ray Diffraction (XRD)*

XRD was used to determine the mineralogy of the pigment materials. Data collection was carried out by Professor Damian Gore, and Mr Russel Field. Diffractograms were collected from 5^o–95^o 2θ using a PANalytical X'Pert Pro MPD diffractometer, with operating conditions of 40 mA, 45 kV, CuK_α radiation, in Bragg Bretano geometry.

3.3 Carbon dating

A small portion of barely-attached wrapping was carefully isolated and removed from the mummy, along with fragmentary material that had previously fallen off the specimen, and a sample of fur which was extracted through an opening in the wrappings located at the base of the mummy. Samples were weighed (Table 5) and placed in separate vials (Figure 21), prior to sending to Beta Analytic Inc., in Miami, Florida. Method of analysis is as follows, according to information shared by Beta Analytic Inc: the samples were washed with hot HCl acid, followed by NaOH alkali wash to remove secondary organic acids. A final acid rinse is used to neutralise the materials before drying. Following treatments, samples are reduced to graphite (100%), and then analysed for carbon 14 content in an Accelerator Mass Spectrometer (AMS). The results are corrected for isotopic fractionation and converted into a calendar-calibrated date.

Sample no. (Beta Lab.)	Material	Weight
Beta-473336	Fur/skin	11.2 mg
Beta-473337	Textile	3.0 mg

Table 3. Sample information for radiocarbon dating.

4 Results

4.1 Neutron Tomography

Visualisation of the mummy in 3D (Figure 22a) depicts the outer wrapping of the specimen, however does not show the painted markings. Though the markings are not apparent, the direction of the narrow bandage is more defined. It appears to wrap downward, in a spiral clockwise direction, and when it reaches the base, it is flicked back up and secured.

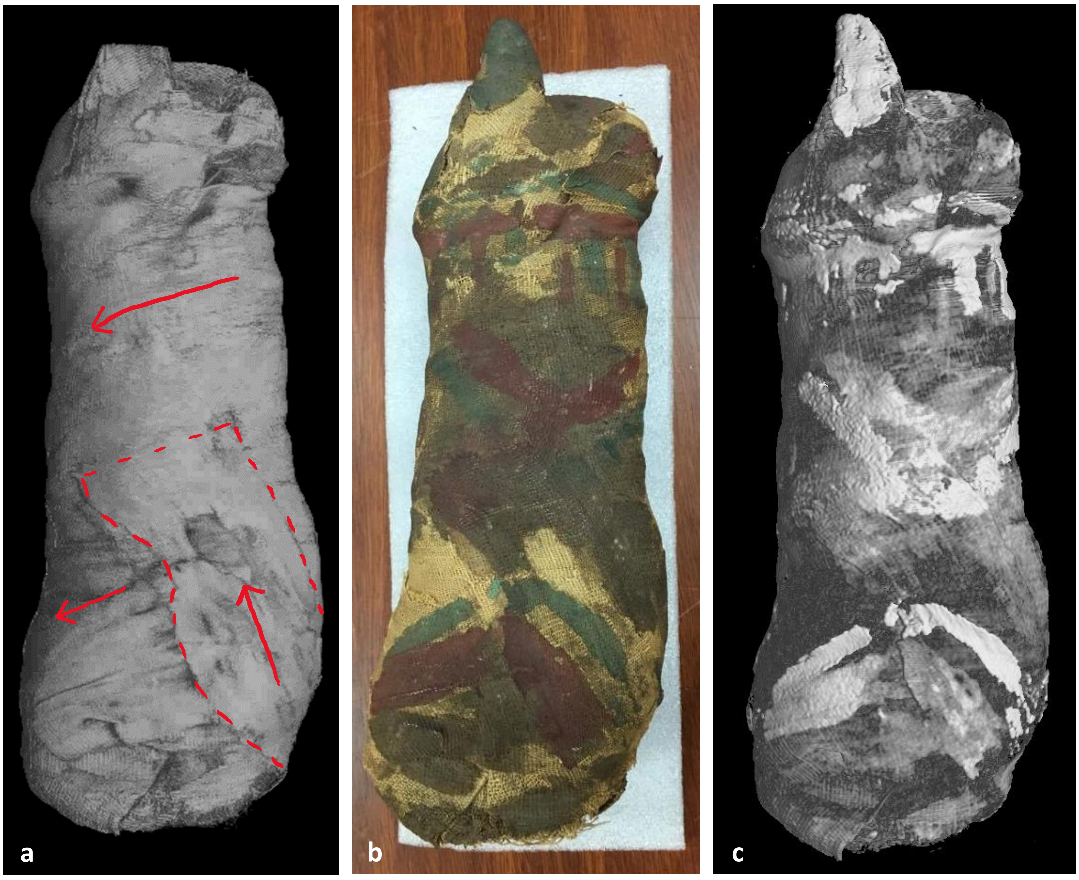


Figure 22. ***a)*** External appearance of 3D reconstructed neutron CT data (*red arrows indicate wrapping direction*); ***b)*** Photograph of mummy for comparison. ***c)*** External appearance of X-ray CT 3D reconstruction .
Videos of 3D reconstruction available for: X-ray https://cloudstor.aarnet.edu.au/plus/f/1714806813 *and* Neutron CT https://cloudstor.aarnet.edu.au/plus/f/1714806743 .

Reconstructed tomographs revealed an incomplete, partial skeleton, and desiccated flesh, encased in the wrappings (Figure 23). There is little density contrast between bone and textile, however both were discernible in the visualisation. The skeleton of the animal sits vertically in the wrapping, starting just below the 'neck' (Figure 23), and ending at the base, visible from the opening described previously. The bones present appear to be two hind legs, and an articulated, broken tail. There is no visible trace of a spine, ribcage, skull or fore-limbs.

The 3D reconstructed volume of the mummy also revealed areas of 'padding' and layers of textile (Figure 23). These reconstructions show two different textile layers according to their density, possibly due to varying coarseness of the textile or how tightly they are wrapped around the bones. The inner-most wrapping is brighter and more densely wrapped than the outer. The outer layers appear to have considerably more space between the layers and even threads, than the inner textile. It is possible to note the coarseness of the threads on the outer layers, seen as 'dots' where wrapping direction has been intersected.

In the upper section of the specimen, the bones appear securely wrapped, with extra textile above, containing no objects. It appears to be solely to make the shape of a skull. The lower section of the specimen is less padded, with little to no textile around the very base where the opening is located; as such, the remains of the animal are less secured and more prone to mobility. In the lower section, there is a thick, bright outline that is not associated with the wrappings. Within the outline is a dark, void-like space, in which the bones sit. This bright outline signifies a more dense or hydrous material, such as the skin of the animal.

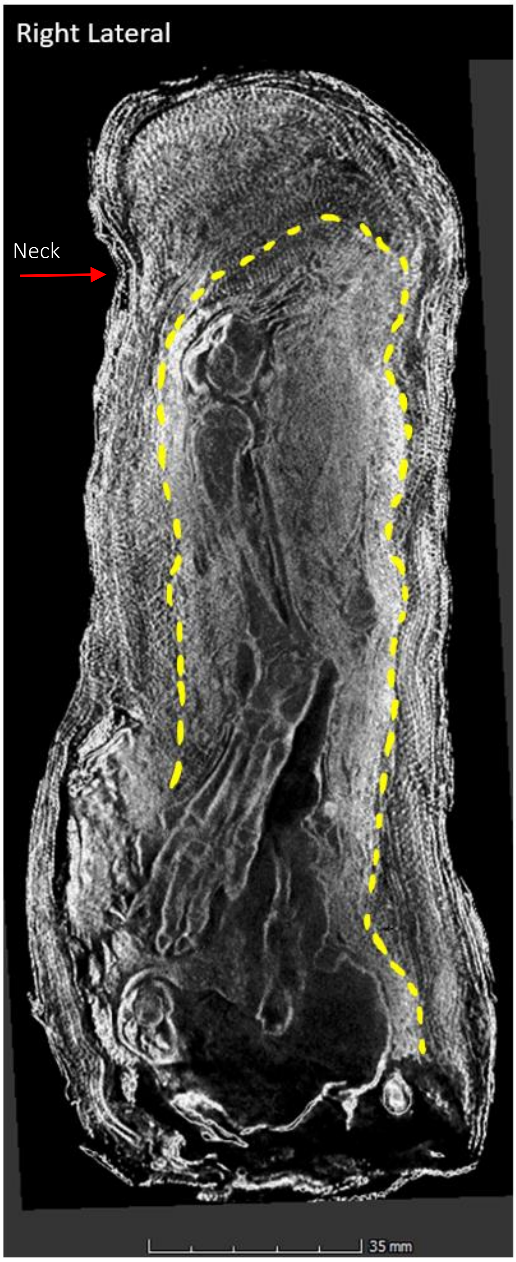


Figure 23. Cross section of reconstructed neutron CT data. *Yellow dashes mark area of denser wrapping. Red arrow shows 'neck' of the mummy.*

4.2 X-ray CT

The X-ray data, once reconstructed, also revealed a partial skeleton, with a higher density contrast between textile and bone in X-ray results than neutron CT (Figure 24 and 27). There is a clear difference between the inner and outer layers in the X-ray data, showing higher density in the inner wrapping (light grey in Figure 25). The direction of wrapping is not discernible in this data, neither is the coarseness of the textile.

There are thin, irregular layers of very highly attenuating areas identified and confined to the outermost wrapping of the mummy (Figures 24, 25, and 26). Visual inspection of the specimen shows a correlation between these regions with the green painted markings on the outermost bandages (Figure 22c). The green paint is much brighter than the red meaning, and to have such high attenuation to X-rays, the paint must contain a compound of a heavy element as a component. This observation will be expanded upon in the pigment-analysis section. All collected X-ray CT data revealed a small, highly X-ray attenuating, amorphous object within the wrapping, close to the paws (Figure 25, and 26). This was not initially observed in the neutron tomographs, suggesting it may be metallic. This small object measures 4 x 2 mm.

There was notable difference in the clarity the image produced by the different techniques: Cone Beam CT (CBCT), Dual Energy CT (DECT) and Multi Detector CT (MDCT). Cone beam results showed the layers of textile in some detail (Figure 25), with similar outcomes for the Dual energy results (Figure 24). The two Multi detector scans had very different results (Figure 26), with the smaller scan (396 slices) producing blurry, over-exposed images.

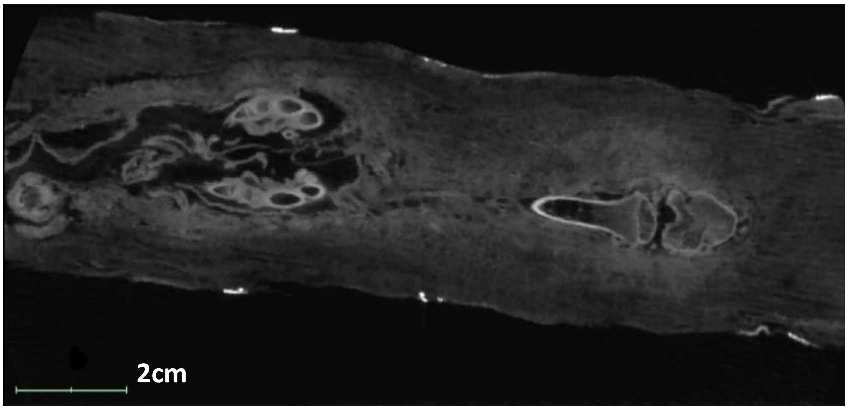


Figure 24. X-ray CT slice (DECT) showing the wrapping and the bones encased.

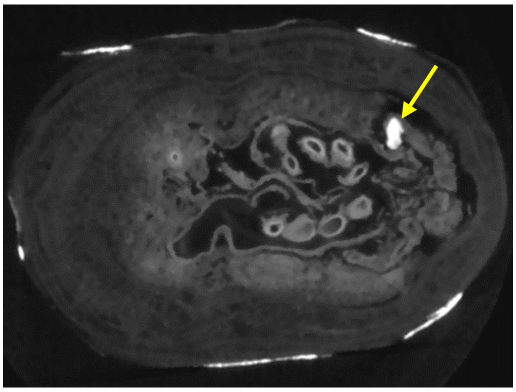


Figure 25. X-ray CT slice (CBCT) showing the wrapping, metatarsals and small amorphous object *(marked by yellow arrow).*

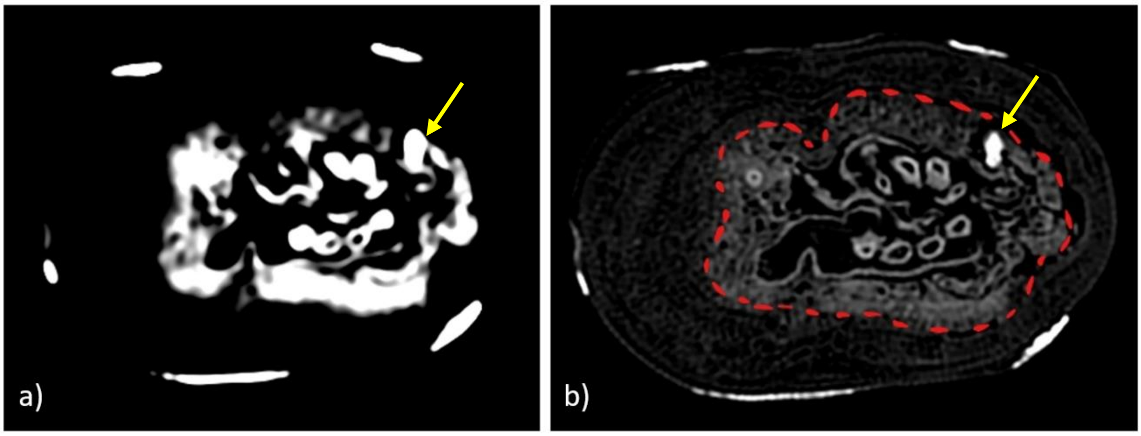


Figure 26. ***a)*** MDCT scan 1 (396 slices); ***b)*** MDCT scan 2 (792 slices). *Red dashes mark change in textile density; Yellow arrow marks small amorphous object.*

Figure 27. X-ray CT (MDCT) 3D reconstruction of animal bones (rotated), created using RadiAnt DICOM viewer.

4.3 Scanning Electron Microscope *(SEM)*

Red Pigment

Whole images of the sample were captured in secondary electron (SE) and backscattered electron (BSE) images (Figure 28). The red pigment appears thick, and densely packed. The BSE images show that there are semi-prismatic mineral fragments, of varied size, across the sample. The spin of threads is not as visible in this sample, as the pigment is thicker. The results of energy dispersive spectroscopic (EDS) analysis (Figure 29) are shown as a RGB pseudo colour map, with a corresponding table of whole sample spectra (Table 5). When overlaying the elemental maps for this sample, Ca and S are clearly associated, depicted in the purple colour which indicates the presence of calcium sulfate. Spot analysis shows that there are also traces of iron and silicon (Table

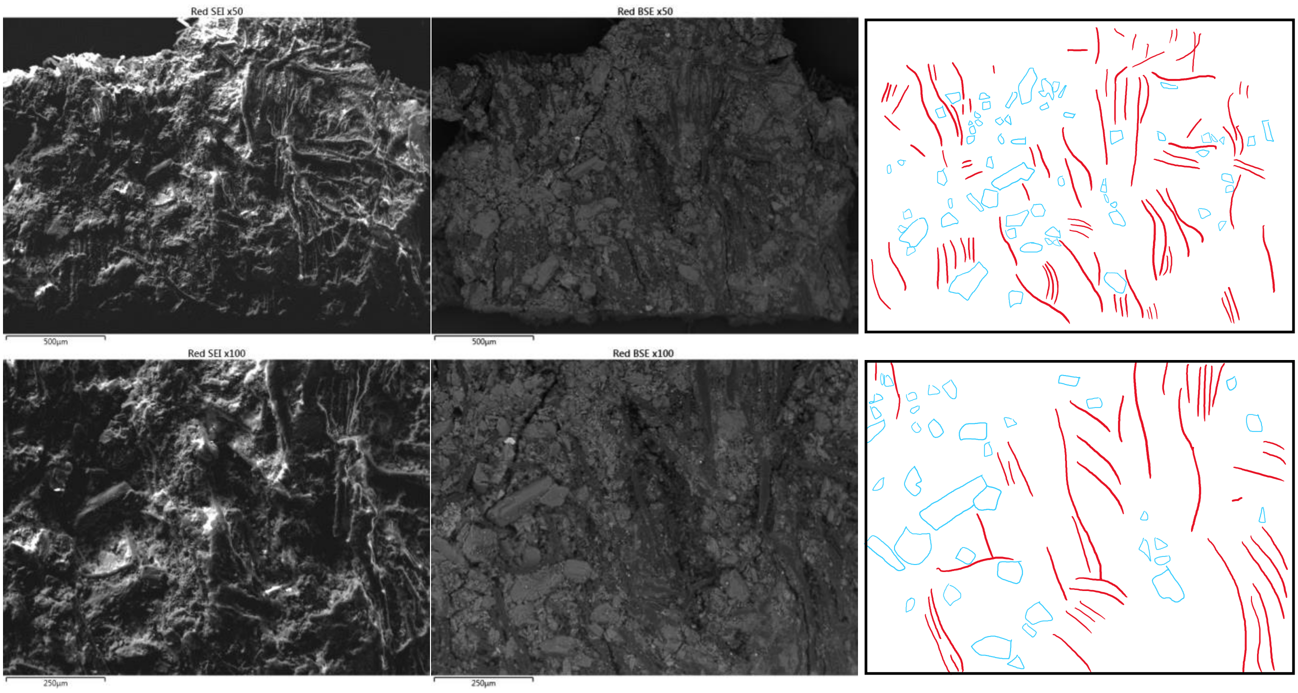


Figure 28. Secondary electron images (SEI) and back-scatter electron images (BSE). Sketches illustrate thread direction (red), and larger mineral fragments (blue). Images taken at increasing magnification on sample *C1* site 1.

6). Multiple spot analyses were taken across the sample to identify where iron has accumulated (Appendix 3).

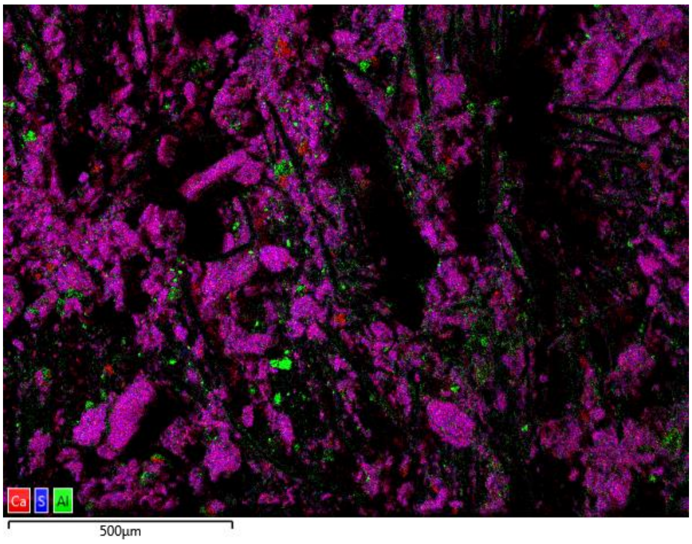


Figure 29. A pseudo colour RGB map showing distribution of calcium in red (*Ca*), sulfur in blue (*S*) and aluminium in green (Al) across the red pigment sample.

Red_Map	Wt%	Wt% Σ
O	54.44	0.07
Na	0.79	0.02
Mg	0.92	0.01
Al	1.61	0.01
Si	3.79	0.01
P	0.09	0.01
S	12.17	0.02
Cl	0.79	0.01
K	0.57	0.01
Ca	17.1	0.03
Ti	0.2	0.01
Fe	7.02	0.02
Zn	0.51	0.02
Total	100	

Table 4. Elemental abundance based off EDS spectra. High abundance of Ca and S correlate with presence of calcium sulfate noted in Figure 29.

Figure 30. Secondary electron image, Point analysis taken at red dot shows elemental data (table 6) for red pigment material.

Site 1_Red	Wt%	Wt% Σ
O	57.3	1.31
Si	0.9	0.16
S	17.46	0.64
Ca	22.86	0.78
Fe	1.48	0.29
Total	100	

Table 5. Elemental analysis for Site 1_Red. Note high abundance of calcium (Ca), and sulfur (S).

Green Pigment

Whole images were taken, as well as SE and BSE at increasing magnifications. This data reveals that the pigment material is a pigment, rather than a dye, as the coloured material correlates to the blocky fragmentary material, seen in the outlined blue fragments (Figure 31). These fragments tend to accumulate where the threads of yarn crossover (Figure 31, right-most column). The SEM images (Figure 31) also allow for detailed observation of threads comprising the wrapping. The fibres are S-spun (illustrated in red, this shows the curve of the threads in ‘s’ shape), as was noted from the optical techniques in the initial observations section. The ultimate fibres exhibit longitudinal striations, which would confirm that the main component of the mummy wrapping is flax fibres.

EDS analysis is shown as an RGB (red, green, blue) pseudo colour map (Figure 32); the detected elements and their proportions are listed in Table 7. When overlaying the three elemental maps for barium (Ba), sulfur (S) and calcium (Ca), it can be seen that there is an abundance of Ba and S, and that they are associated with each other depicted in the yellow colour, indicates the presence of barium sulfate. Ca and S are also associated, depicted in the teal colour which indicates the presence of calcium sulfate. Considering the green colour of the pigment, it had been assumed that this would be due to a copper compound. However, following spot analysis (Figure 33), only few appearances of copper were found (Table 8). Additional spectra can be found in Appendix 4.

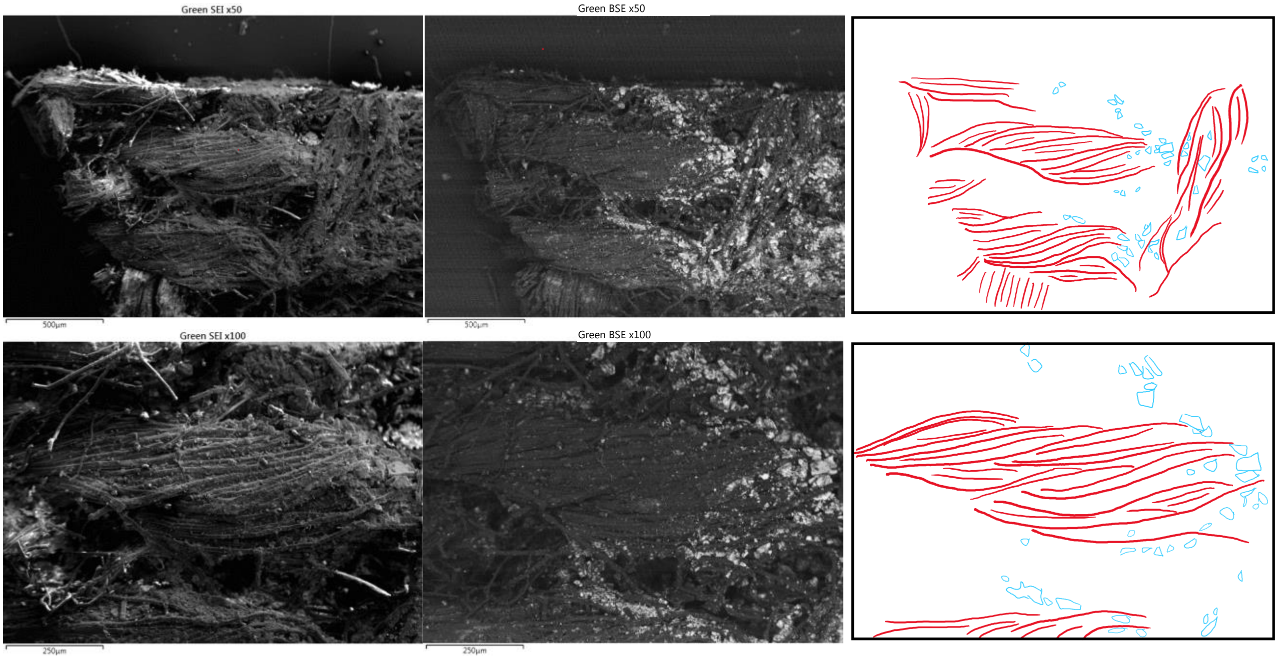


Figure 31. Secondary electron images (SEI) show the fibres in great detail, while back-scatter electron images (BSE) show more information about the distribution of the pigment material. Sketches illustrate spin direction of the threads (red), and mineral fragments (blue). Images taken at increasing magnification on sample *B1* site 1.

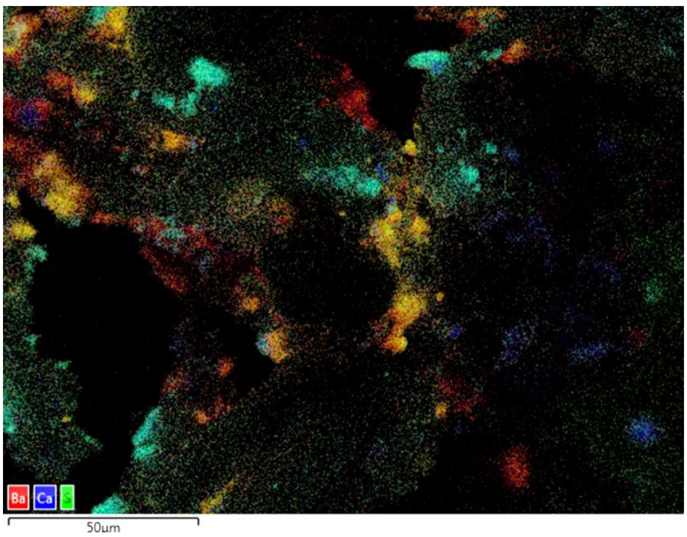


Figure 32. A pseudo colour RGB map showing distribution of barium in red (*Ba*), Sulfur in green (*S*) and Calcium in blue (*Ca*) across the green pigment sample.

Green_Map	Wt%	Wt% Σ
O	12.23	1.22
S	15.9	0.73
Cl	2.62	0.4
Ca	1.2	0.31
Ba	68.05	1.27
Total	100	

Table 6. Elemental analysis derived from EDS spectra. High abundance of Ba and S correlate with presence of barium sulfate noted in Figure 32.

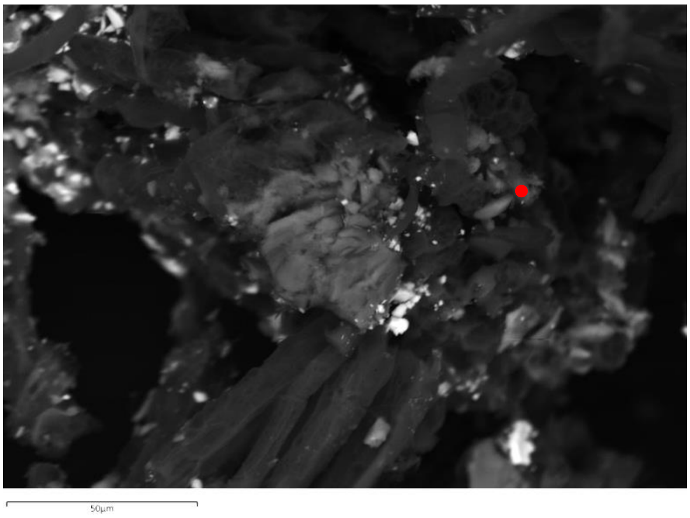


Figure 33. Point analysis taken at red dot illustrates presences of copper (Cu). Elemental analysis is broken down in table 8.

Site 1_Green	Wt%	Wt% Σ
O	43.39	0.47
Na	0.85	0.14
Mg	0.36	0.08
Al	0.87	0.08
Si	5.73	0.12
S	3.31	0.09
Cl	1.54	0.08
K	5.33	0.12
Ca	9.05	0.15
Fe	9.08	0.22
Cu	16.8	0.32
Ba	3.69	0.3
Total	100	

Table 7. Elemental analysis by weight percent for Site 1_Green, shows presence of copper (Cu), as well as silicon (Si), iron (Fe) and calcium (Ca).

4.4 Raman Spectroscopy

Red Pigment

Sample *C1* produced a Raman spectrum shown in red in Figure 34, which is characteristic of gypsum ($CaSO_4$) according to the RRUFF Raman database (Lafuente *et al.*, 2015). The presence of gypsum correlates with the presence of calcium sulfate as suggested by the elemental data collected on the SEM from this sample (Table 5). There is some shift in the Raman peaks, which is not due to a calibration issue, as the spectra for both green and red pigments were collected shortly after each other. Iron (Fe) is present in the red sample (7 wt%) and it may be the cause of peak shift. This will be discussed further in the section following.

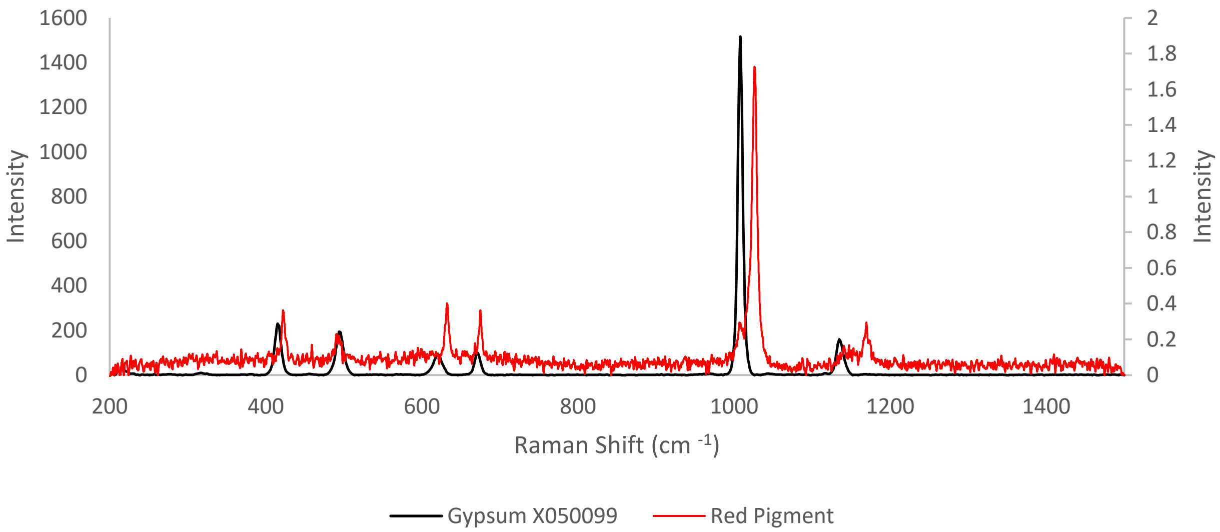


Figure 34. Raman spectra for Red pigment study. Corresponds with gypsum R040029 spectra from the RRUFF database. *Y-axis for red pigment results on right side.*

Green Pigment

Sample *B1* gave the spectrum shown in green in Figure 35, which is characteristic of baryte ($BaSO_4$), according to the RRUFF Raman database. This correlates with the elemental data listed in Tables 7 and 8, which show an abundance of barium and sulfur in the sample. The peak positions correlate well, except for the unidentified peak at ~650 cm^{-1}.

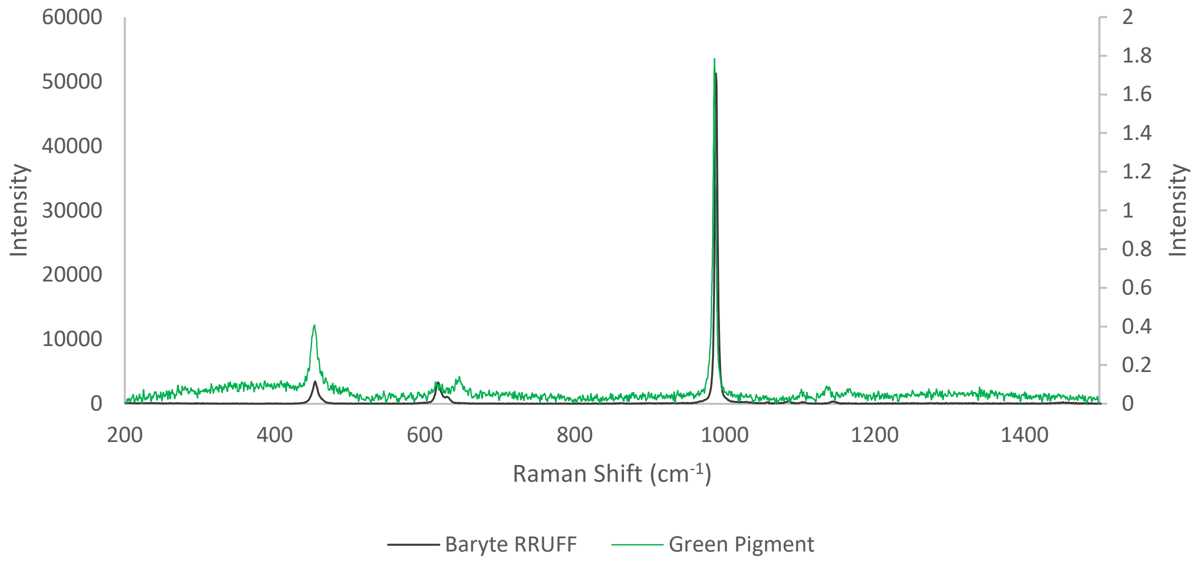


Figure 35. Raman spectra for Green pigment study. Peaks match with baryte (R040036) standard Spectra from the RRUFF database. *Y-axis for green pigment results on right side.*

4.5 X-ray Diffraction (XRD)

Minerals present in the samples were identified by comparison of acquired XRD patterns with those in the RRUFF and MINDAT databases. Both green and red pigment samples contain cellulose, associated with the textile. Red pigment contains gypsum, calcite, quartz, and hematite (Figure 36). The green pigment (Figure 37) contained baryte, cuprorivaite and quartz.

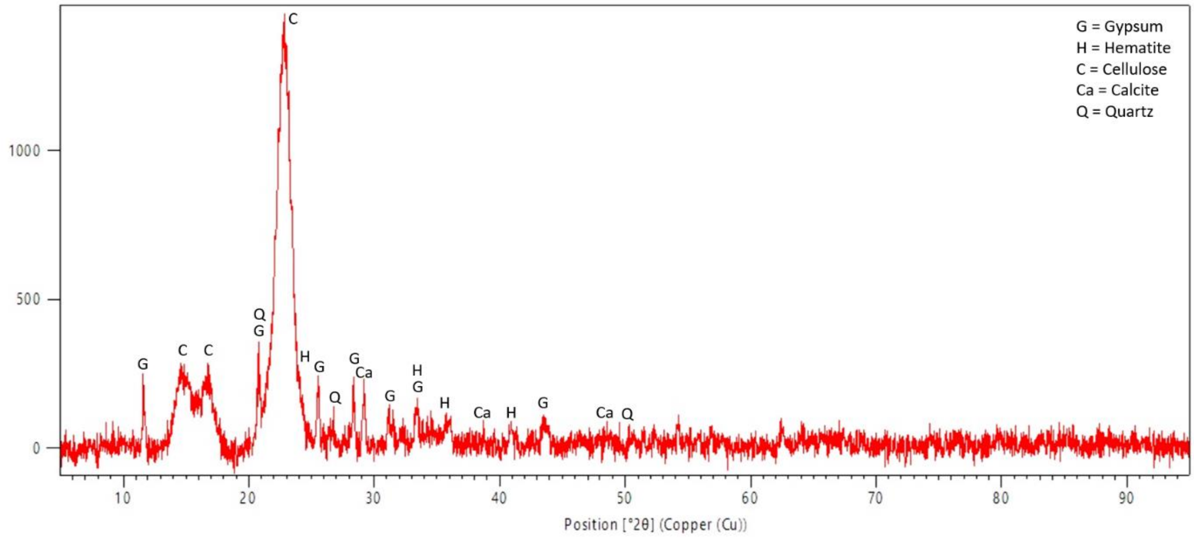


Figure 36. XRD spectra for red pigment sample.

Peaks labelled manually, and matched to various RRUFF XRD spectra (Gypsum R060509.1; quartz R040031.1; hematite R040024.1; calcite R040070.1). Cellulose matched using Chen et al., (2013).

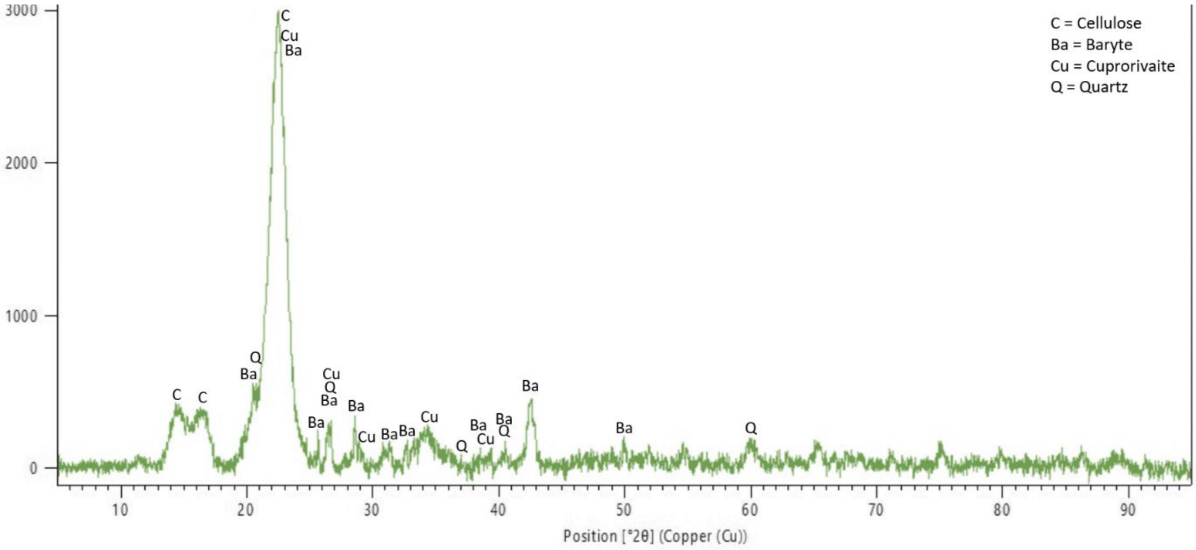


Figure 37. XRD spectra for green pigment sample.

Peaks labelled manually and matched to various RRUFF XRD spectra (Baryte R040036.1; quartz R040031.1.); Katsaros and Liritzis, (2011) for cuprorivaite. See Figure 36 for organics reference spectra.

4.6 Radiocarbon dating

Prior to analysis, sample Beta-473336 was re-categorised as ‘plant material’ by Beta Analytic, as there was a large amount of plant material present (Appendix 5). Following Accelerator Mass Spectrometry (AMS) dating, the results showed that the mummified remains, mixed with plant material (Beta-473336) were 2690 ± 30 BP (before present), placing it between 900 – 804 BC to 95.4% probability (Appendix 6). The external wrapping sample (Beta-473337) is approximately 500 years younger than the encased remains, dating to 2230 ± 30 BP (367-204 BC), between the Late Period and Ptolemaic Period (Appendix 6).

5 Discussion

5.1 Osteometry and Speciation

X-ray and neutron 3D visualisations allowed non-destructive imaging of the internal contents of the specimen. This provides the opportunity to better determine the species, age, sex and domestication of the mummified animal. The bones visible in the X-ray and neutron CT results included a femur, two fibulas, one tibia, two sets of metatarsals complete with claws, and an articulated tail. The presence of these hind limbs, coccygeal and caudal vertebrae indicated that this mummified specimen is the rear of a small mammalian digitigrade.

The tail has been broken, most likely post-mortem. The remains are extremely decayed, and it is difficult to determine the presence of some coccygeal and caudal vertebrae, however there were approximately 23 present (Figure 38). This indicates that it is most probably a Felid, as they typically have 19-23 caudal vertebrae. This inference is supported by the morphology of the components of the skeleton, which are consistent with that of genus Felis (T Fothergill, personal communication, 24 May 2017). It is therefore concluded, based on these observations, that the animal encased in the wrappings is a feline.

Figure 38. Caudal vertebrae annotated in red, 23 present.

The age of the animal at the time of death can be determined by observing the growth plates (epiphyses) between bones. The reconstructed neutron data revealed that there was partial-fusion of bones in the left hindlimb (Figure 39). These were also visible in the reconstructed X-ray data (Figure 39). The state of the epiphyses between the distal metatarsals, proximal tibia and distal femur indicate that the animal had not yet reached adulthood when it died. This would suggest that the mummified animal was a juvenile or subadult cat, younger than 11.5 months old (T Fothergill, personal communication, 24 May 2017). The state of the epiphyses depends on whether the animal was domesticated or from the wild. Typically, wild animals experience fusion of growth plates at a later stage, near to or following one year of age (Habermehl, 1985; Van Neer *et al.*, 2014); domesticated animals tend to experience this earlier (Habermehl, 1980; Van Neer *et al.f*, 2014). It is therefore possible to conclude that this was a domesticated cat.

Figure 39. X-ray (Left) and neutron reconstructions showing epiphyses (red arrows).

Classifying the species based on visible features in the CT data is difficult due to the juvenile nature of the cat, and absence of many key features that would hint to the species, such as skull shape and size, as discussed by Johansson *et al.* (2015). An additional indicator of species type is based on tail length, as longer tails (320 mm) are characteristic of Felis silvestris, and shorter tails (250 mm), Felis chaus (Johansson *et al.*, 2015). However, the lengths recorded by Johansson *et al.* (2015) are those of adult cats, and this case study is not in the same category, as previously established. The length of the tail of this mummy is approximately 126 mm, falling short of his parameters for either species.

The shape and size of the calcaneus is also characteristic of particular species. These bones are present in the left limb more clearly than in the right. While the 3D reconstruction of the X-ray data shows that they are extremely decayed (Figure 28), using VG studio, the bone was segmented to reveal a definitive shape (Figure 40). Comparing the shape and size of the bone with that mentioned in Van Neer *et al.*, (2014) for mummified adult cat skeletons, there is more resemblance to the calcaneus of Felis silvestris than that of Felis chaus. The sizes do not correlate which could be due to this specimen being a juvenile.

Figure 40. a) Neutron and b) X-ray data showing location of calcaneus (red arrow). c) Shapes of calcaneus in adult cats (Van Neer et al., 2014); d) Calcaneus extracted manually from X-ray CT data using VG Studio. Video of calcaneus 3D reconstruction available https://cloudstor.aarnet.edu.au/plus/f/1714807083.

The shape of the calcaneus was also examined to indicate gender (Van Neer *et al.*, 2014). The shape of the bone is closer to that of the female due to the wider flare of the socket (Figure 40 c and d). Additionally, there is no baculum (penis bone) found within the wrappings, which could suggest that the cat was female, or that this bone for some reason not included, as there is no pelvis in the wrappings either. There are no clear signs of inflicted trauma on the legs and tail that may have killed the animal. Generally animals received a sharp blow to the head, or twisting and snapping of the neck (Armitage and Clutton-Brock, 1981; Ejsmond and Przewlocki, 2014;

Johansson, Metz and Ulhorn, 2015) when they were euthanised. In this case, it is not possible to identify these features, so no indication of the cause of death can be established. Overall, the results showed that this animal is a female juvenile cat of the species Felis silvestris.

5.2 Radiocarbon dating:

Knowing that the mummified cat remains are approximately 500 years older than the bandages that surround them, this suggests that the animal remains have been re-wrapped at the end of the Late period (664-332 BC). This poses several questions: 1) what was the original state of the remains: were they partial or a whole skeleton? There are two possible scenarios, the first being that the remains were originally a complete feline skeleton, or the second, that the original state was as it is now, a partial skeleton. If the animal had originally been wrapped as a complete feline skeleton in the Third Intermediate Period, and was divided in the Late Period, post mortem, there would be evidence that the animal had been broken apart, i.e. damage to hard and/or soft tissue, fractured bones or jagged edges on bones. Examining the X-ray and neutron CT data, no signs of post-mortem trauma or damage are visible. The end of the femur does not exhibit evidence of jagged breaking, and no evidence of soft tissue trauma. Aside from the broken tail, there does not appear to be any sign of post-mortem forceful manipulation of the skeleton. Additionally, the epiphyses are still intact, which suggests that there has been no direct post-mortem interference with the remains. The remains would have been very fragile after 500 years, and prone to breaking or disarticulating with excessive handling or interference.

It therefore seems that the legs and tail of this mummy are the original remains, and have been re-wrapped in the Late - Ptolemaic period. As previously mentioned, this was a time of high demand for mummified votive offerings at temples, and the manufacturers and embalmers were struggling to keep up with this demand (Kurushima *et al.*, 2012; Ejsmond and Przewlocki, 2014; Petaros *et al.*, 2015). When the mummy was first made, Egypt's capital would have been either Tanis or Bubastis in the Nile Delta (900-800 BC), in both cities there are major votive animal cemeteries dedicated to cats (Ikram, 2015; Zivie and Lichtenberg, 2015). Fast forward 500 years to the end of the Late period, and Egypt's capital had been relocated to Sebenytos (380-343 BC), then Alexandria from 332 BC until 641 AD (Lloyd, 2000a, 2000b), quite close to these older burial grounds. It is thus possible to suggest that the old catacombs of these animal cemeteries may have been pillaged, as many tombs were, for amulets and grave goods (Nicholson, Ikram and Mills, 2015), and the disturbed remains may have been re-wrapped and re-sold. By re-wrapping the mummies in new bandages, and in this case, painting them, they are made to appear new, and pilgrims wanting to purchase votive offerings at the temple would not have known the difference.

5.3 Mummification technique

Neutron CT reconstruction has made clear a few interesting features in the process of votive animal mummification. Primarily, it has allowed for viewing of the internal structure of the mummy, and has revealed that there are two layers of wrapping – one tightly wrapped around the tail and legs specifically, and a second that encompasses the padding and bones. The inner layer appears as a denser mass, and a much finer textile than those of the outer wrapping, observed in the individual threads that make up the weave that are closer together and smaller than the outer layer. This finer textile has been tightly wrapped around the bones, evidenced by the lack of spaces between the layers. The number of layers is not discernible at this resolution, however more detailed investigation of the inner textile would be possible using neutron CT at higher resolution, although this would require longer exposure times and further irradiation.

The second, outer layer is also clear in the reconstructions, having been wrapped around the mummy approximately eight times (Figure 41). These observations agree with observations made by Ginsburg (1999), in unwrapping of mummies from the Bubasteion at Saqqara. He reported that for smaller animal bundles, there were only ever two layers of bandages, one tight around the bones, and a second like a shroud around the bundle. The outer textile exhibits a corkscrew style of wrapping, as previously mentioned and illustrated (Figure 23), and this is a technique reported by Ginsburg (1999).

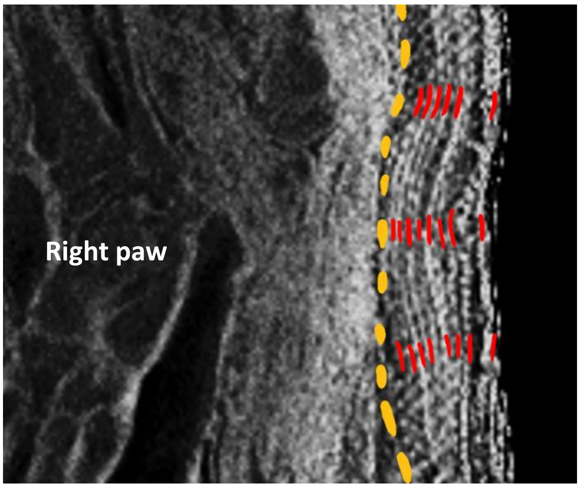


Figure 41. Neutron radiograph showing layers of textile. *Red lines indicate layers of wrapping, and yellow line shows boundary between inner and outer wrappings.*

Looking more closely at the top half of the mummy, the reconstructed neutron radiographs show a folded wad of fabric in the 'head' section (Figure 42). There are no bones present in this part of the mummy, and thus the fabric appears to have been used to shape the inner bundle, to appear as a complete cat. In addition to this padding, the ears of the mummy are also made of folded textile, containing no animal remains. This practice was not uncommon, with several examples of mummies being made to look larger or even like a different animal using padding (Ejsmond and Przewlocki, 2014). The purpose for such could be interpreted as to make the animal look bigger, as a grander gift to the Gods.

There is very little padding or textile at the base of the mummy, which could suggest that the animal was wrapped from head down. Noting the folded wad in the head of the mummy, it seems that this was made after the legs and tail were wrapped, and placed atop the bundle, to give

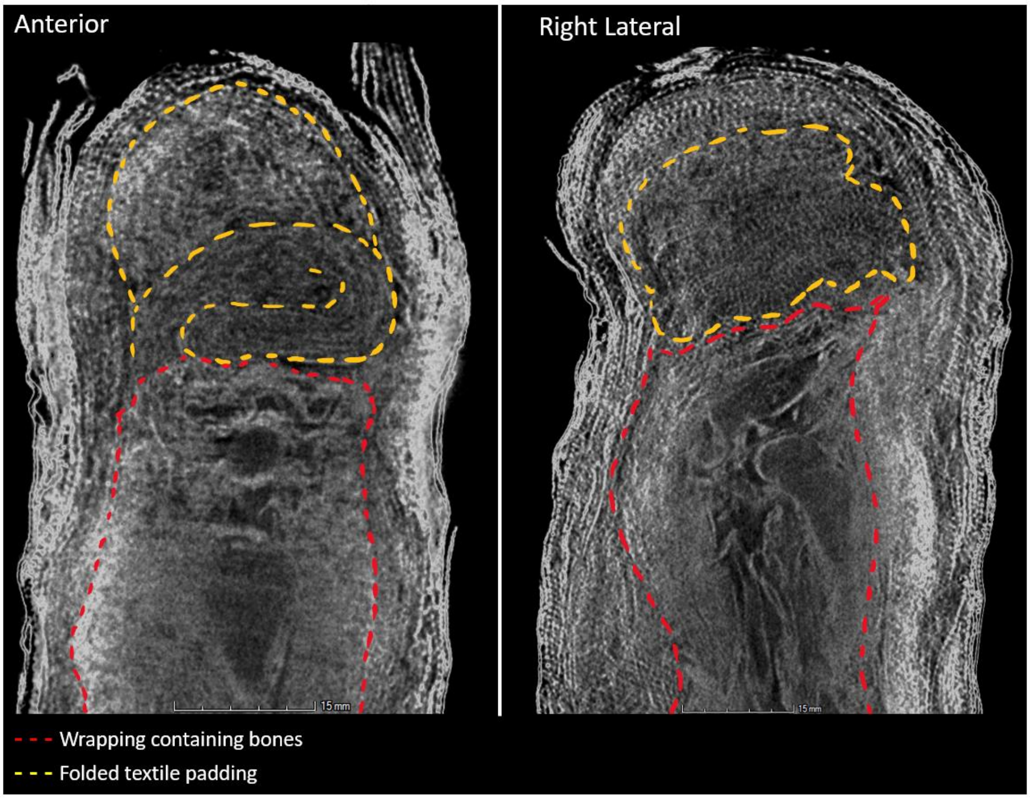


Figure 42. Illustrations drawn onto neutron radiographs.

Yellow shows areas of textile encasing no bones or media, which appear to be folded layers of textile. The red shows wrapping containing bones and animal remains.

the illusion of a complete animal, adding size and shape. As this folded wad of fabric in the head appears to fit the tightly wrapped bones so well, it may be that this was also part of the original bundle, with just the external wrapping having been replaced. Within this area is a bright outline, observed in X-ray and neutron CT reconstructions, which is most likely to be the skin of the mummified animal, and the dark area within that is likely left behind by the decomposed body of the animal. Beside the paws of the cat is a small, highly X-ray attenuating, irregular shaped object (Figure 25, and 26). This was not observed in the neutron tomographs, suggesting it is metallic. It is likely to be an amulet intentionally wrapped with the remains, carrying religious significance, as this was a common practice (Ejsmond and Przewlocki, 2014). Based on the comparative attenuation between thermal neutrons and X-rays, and between the paint in the X-ray data, the object is determined as being composed of a heavy metal such as lead (Bevitt, J., 2017, personal communication, 3 September 2017). Sometimes lead amulets were used to ward off 'sluggish evils' and vermin, as it was considered a heavy 'sluggish metal' (Petrie, 2016). A 3D reconstruction of the object was made, but there was no clear shape or design noted (Appendix 7).

The hole in the base of the mummy is likely the result of human interference, through a cut made in the bottom, similar to the case mentioned by Ejsmond & Przewlocki (2014). One of the cat mummies discussed in their paper has an opening in the base, similar to that seen in this case study, which they suggested could have been made by someone looking for amulets. While this is possible and would have caused damage to the internal textiles of the mummy, it is more likely in this case that the damage has been caused by rough treatment, causing the fabric to tear or rip.

Due to the partial nature of the mummy, as well as the irregular markings and simple wrapping style, it is justifiable to conclude that this was not the pet of a royal or nobleman, nor would it have been a sacred mummy, for much the same reasons. Considering also that cats were not made into victual 'meat mummies' (Ejsmond and Przewlocki, 2014), this mummified specimen can be categorised as a votive offering, confirming the initial hypothesis.

5.3.1 *A comparison of techniques: X-ray and neutron computed tomography*

A primary aim for this project has been to establish neutron tomography as a routine technique in archaeometry, and it is therefore important to address the strengths and weaknesses of the technique displayed in this study, particularly in relation to X-ray CT. Overall, neutron tomography has excellent ability to image and reconstruct textile layers (Figure 41), providing unrivalled insight into how animal remains were wrapped. While X-ray CT showed that a clear density difference between the inner and outer wrappings, it did not match the detail of the textile layers that can be seen in the neutron CT radiographs. With advancements in neutron CT data collection since the acquisition of the data used here would now be possible to image the inner wrapping at higher resolution and potentially digitally unwrap the cat (Bevitt, J., personal communication, 3 September 2017). This project has clearly illustrated the strengths of neutron tomography for studying mummification wrapping techniques.

Both neutron and X-ray CT were useful in studying the skeleton inside the wrappings. X-ray CT, due to higher X-ray attenuation for bone and metal, produced better radiographs of the skeleton than neutron CT, which has strengths in hydrogenous and organic materials. As this sample is almost entirely organic, there was little density contrast between bones and wrapping in the neutron CT, compared to the high-density contrast seen in X-ray CT radiographs. Despite this, both techniques showed epiphyses between bones, which was ultimately helpful for identifying the age of the cat at its death. The advantage to using X-ray CT is that it is a well-established technique, in both the archaeometric and medical fields, and it has pre-set filters and programs that make analysis of X-ray CT data simple and accessible. This enabled fast, accurate reconstruction of the data with relative ease. Neutron CT data reconstruction is time consuming, due to the absence of pre-set filters or algorithms (to date), reconstructions and segmentations are done manually, which is slow and laborious.

X-ray CT showed strengths for identifying metallic materials within, and on, the wrappings. Most notably, X-ray CT reconstructions revealed a small high X-ray attenuating artefact, likely made from a heavy metal, by the paws of the cat. The neutron CT data did not clearly show the presence of this small metallic artefact. Additionally, X-ray CT reconstructions revealed highly X-ray attenuating material, matching the green markings painted on the external of the mummy wrapping which initiated this investigation of the pigments.

As individual techniques, neutron and X-ray CT have their strengths and weaknesses, in some cases, one addresses the limitations of the other. This thesis has demonstrated the synergies of the techniques, and how they combine to give a comprehensive study of mummification process and techniques that can be utilised, demonstrated in Figure 43.

Figure 43. Neutron CT data was used to reconstruct the wrappings in 3D (grey), and X-ray CT data was used to reconstruct the 3D bones (red). *Created using VG Studio.*

5.4 Pigment Analysis and markings

After an exhaustive review of many museum catalogues and votive mummy collections, it has become clear that this mummified specimen is very unusual. There are painted features on the head that depict eyes, a mouth, and a necklace or a collar. It is not unusual for votive mummies of the Late – Ptolemaic period to have painted faces, however the style of the IA.2402 specimen does not match these examples (Figure 44). Of particular interest is the necklace-collar detail, as this may be a symbol for domestication of felines in Egypt, much like the modern-day collar. In addition to these are the markings on its sides. These could be interpreted as the four limbs of the animal. The stylistic choice of using two colours is not uncommon either, however typical colours were red and black. The results collected for both pigments samples (*B* and *C*) revealed various minerals as the base and colour agents.

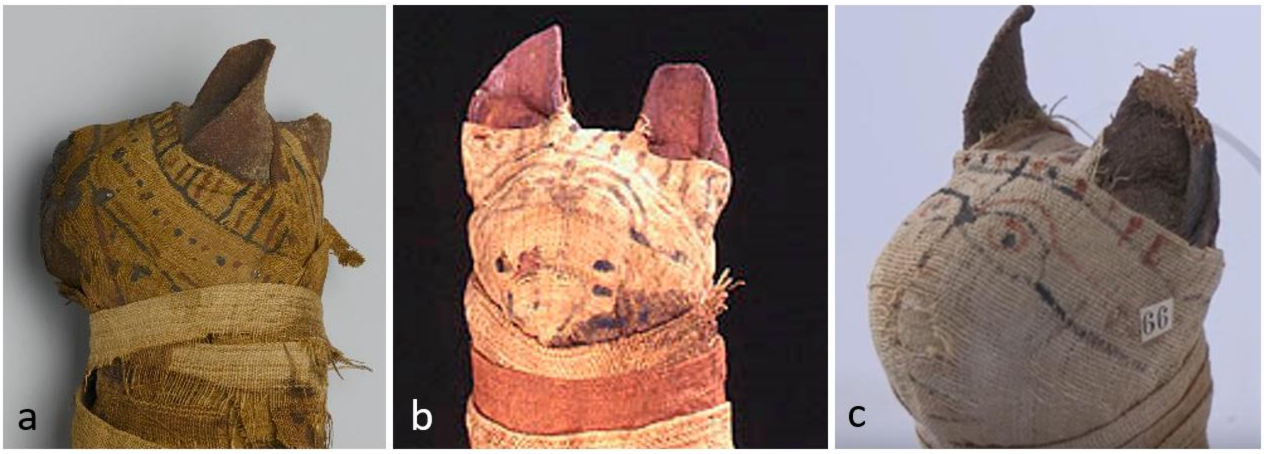


Figure 44. Examples of painted faces on cat mummies from the Late and Ptolemaic Periods. a) Brooklyn Museum collection 05.307; b) McClung Museum collection 73718; c) Aberdeen University collection ABDUM:M.J.3.

Red in Egyptian art and culture

The Egyptians had used the colour red in their paintings and murals since early dynastic times (Barnett, Miller and Pearce, 2006), possibly because it was a colour that could be easily produced by crushing earthy tones, mostly iron oxide i.e. hematite, or red ochre (Fe_2O_3). In later years (1500 BC) more red pigments emerged, including cinnabar or vermillion (HgS), goethite (FeO(OH)), and realgar (AsS) (Rapp, 2009) (Appendix 8.1). Egyptian art was full of symbolism, and each colour has a meaning, depending on the context of its use. Predominantly, red was used in association with high power figures like the Pharaoh, as a symbol of supreme power, command, and protection (Ragai, 1986). Red was further representative of the solar cycle and regeneration, of the evil and chaos associated with Seth (Robins, 2008), and also to represent different sexes, men had red skin tone, while women were more yellow tone (Baines, 1985; Ragai, 1986; Feisner and Reed, 2013). The use of red on the wrapping of this specimen may therefore have connections to regeneration or protection in the afterlife. It was not uncommon to see red paint on votive offerings (Figure 44), as it was an easily accessible colour.

The culmination of EDS results (Figure 29) showed substantial amounts of the elements calcium, sulphur and oxygen, as well as aluminium and iron. Raman spectroscopy was used to isolate specific minerals, that were later compared to the red pigments mentioned above. The mineral showed traces of calcium sulfate ($CaSO_4$), with a small amount of hematite (Fe_2O_3) 20:1, and a small component of quartz (SiO_2). Raman spectroscopy results showed the presence of gypsum ($CaSO_4.2H_2O$). There is a notable peak shift in the Raman data (Figure 36), which is likely due to the presence of iron incorporated into the gypsum. For the Egyptians, gypsum was abundant, also referred to as alabaster (Deer, 1998).

Pigments were made of three main components: extender, colour and binder (Rapp, 2009), and gypsum was often used as an extender in pigment production, as it is a soft white mineral, with tendency to take on colour from impurities. Gypsum was and is abundant in the desert environment (Figure 45), and can be referred to as ‘desert rose’. Hematite (red ochre) peaks were matched in the XRD results, as well as EDS data ratios (Appendix 8.2). Red ochre would give the pigment its distinct earthy red colour. Kaolin and quartz (SiO_2) peaks matched in the XRD and were present in the EDS analysis. Desert rose gypsum formations are abundant in sand, so it is likely that they crushed these crystals to create the extender for the pigment. An unidentified organic binder, potentially egg white, called ‘tempera’, or an organic gum, or animal glue (David *et al.*, 2001; Maurer, Mohring and Rullkötter, 2002; Barnett, Miller and Pearce, 2006; Edwards and Ali, 2011) must have been used to bind the pigment to the textile.

Significance of green in Egyptian art

The colour green in the ancient world was symbol for life and vegetation in the Nile River landscape, a colour for healing, for eternal life, and Osiris, the god of death (Ragai, 1986). As greens were not in common use, perhaps due to scarcity or restriction of resources, they were sometimes replaced by grey (Baines, 1985). Natural sources for green pigment came from minerals with high copper (Cu) content, i.e. malachite ($Cu_2CO_3(OH)_2$), azurite ($Cu_3(CO_3)_2(OH)_2$) or chrysocolla ($Cu_2H_2Si_2O_5(OH)_4.nH_2O$). These minerals were mined in the Sinai region of Egypt since c. 4000 BC (Susarla *et al.*, 2017). Turquoise ($CuAl_6(PO_4)_4(OH)_8.4H_2O$) is also a light green-blue pigment that was used in Egypt, sourced in the Sinai region, and used in Ptolemaic temple art (Marey Mahmoud *et al.*, 2011).

A synthetic green pigment was manufactured from the New Kingdom Period to the 1st century AD, called green frit, or Egyptian green (Bianchetti *et al.*, 2000; Barnett, Miller and Pearce, 2006; Marey Mahmoud *et al.*, 2011). It should also be acknowledged that there was another synthetic pigment being manufactured at the same time called Egyptian blue, the man-made equivalent of cuprorivaite ($CaCuSi_4O_{10}$). Until recently it was thought that Egyptian green was just an alteration of Egyptian blue, fading from blue to green over time, as there was no record of how either compound was made, however this has been disproved (Pagès-Camagna and Colinart, 2003; Pagès-Camagna *et al.*, 2006). Through experimentation, it has been determined that while these pigments are composed of the same materials (silica, calcium carbonate, copper and sodium salt), their respective proportions are different, and higher temperatures are required to create Egyptian green (950^{o}C-1150^{o}C), rather than Egyptian blue (870^{o}C-950^{o}C) (Pagès-Camagna and Colinart, 2003; Grifa *et al.*, 2016). The colour of the blue or green depends on heating and composition ratios, and as a result was rarely the same shade as a previous batch (Pagès-Camagna and Colinart, 2003; Di Stefano and Fuchs, 2011). Therefore, some Egyptian blue appears slightly green according to Cu content and firing temperatures.

The results of the analysis of the green pigment (sample *B*) also showed a combination of minerals and compounds present. EDS analysis (Figure 32) revealed the presence of the elements barium, sulphur and oxygen in substantial abundance, chlorine and calcium were also present. Based on these results, Raman spectroscopy was used to isolate a specific mineral or source (Appendix 8.3). This was done by first isolating a number of options, by examining similar pigment studies, specifically the minerals and pigments: Chinese Blue, malachite, turquoise and baryte. Once collected, Raman spectra were compared to spectra of those minerals and pigments listed above. Raman spectroscopy identified the mineral as barium sulfate ($BaSO_4$), with minor calcium sulfate, this was also confirmed with the use of XRD (Figure 35 and 37). Baryte is a soft, white mineral with resinous properties, which is sometimes, like gypsum, referred to as 'desert rose' but it is softer than gypsum (Deer, 1998). Baryte can occur in different colours according to impurities however in this sample, it seems the baryte is acting as the pigment extender.

The green colour in this pigment has been difficult to conclusively determine, as EDS spot analysis showed there are areas where Cu is more abundant than others, yet the colour is consistent across the sample. XRD analysis did not show the presence of malachite, or azurite. Chrysocolla could be the colour agent in this pigment, however this would be difficult to determine as chrysocolla is amorphous, and does not have an XRD pattern (Hope *et al.*, 2012). This suggests that this pigment may be a synthetic product, such as Egyptian green, or even Egyptian blue. Cuprorivaite was found to match several XRD peaks, and the EDS data showed that the necessary elements are present, and may be the green colour agent (Appendix 8.4). The distinguishing factor that helps discern if this pigment is Egyptian blue and green can be noted in the SEM, as the presence of parawollastonite ($CaSiO_3$) is indicative of Egyptian green (Pagès-Camagna and Colinart, 2003). Parawollastonite is a fibrous mineral with a crystal structure, which was not observed in XRD data collected for this pigment. Egyptian green was also only used between 2100 to 1069 BC (Pagès-Camagna *et al.*, 2006), which does not match with the time frame when this mummy was painted. It is therefore more likely that this is either chrysocolla, or an Egyptian blue that is slightly more turquoise in colour.

5.5 Implications: provenance and cultural significance

The age of the original remains places the cat mummy in the Third Intermediate period (1069 – 664 BC), a time when Egypt was under the control of the Libyans, and Pharaoh Osorkon II (874 – 850 BC) (Taylor, 2000; Kemp, 2006). The political centres were located at Tanis and Bubastis during this period, in the east Nile Delta region (Figure 45). These cities were also the locations of two sacred cat cemeteries: one at Tanis, and one at Bubastis. While the Libyans did not have the same motivations as the Egyptians when it came to building monuments or temples (Taylor, 2000), they did assimilate to religious practice, and evidently animal mummification. Votive animal mummification was not a popular practice at this time, with interest increasing toward the end of the Late Period.

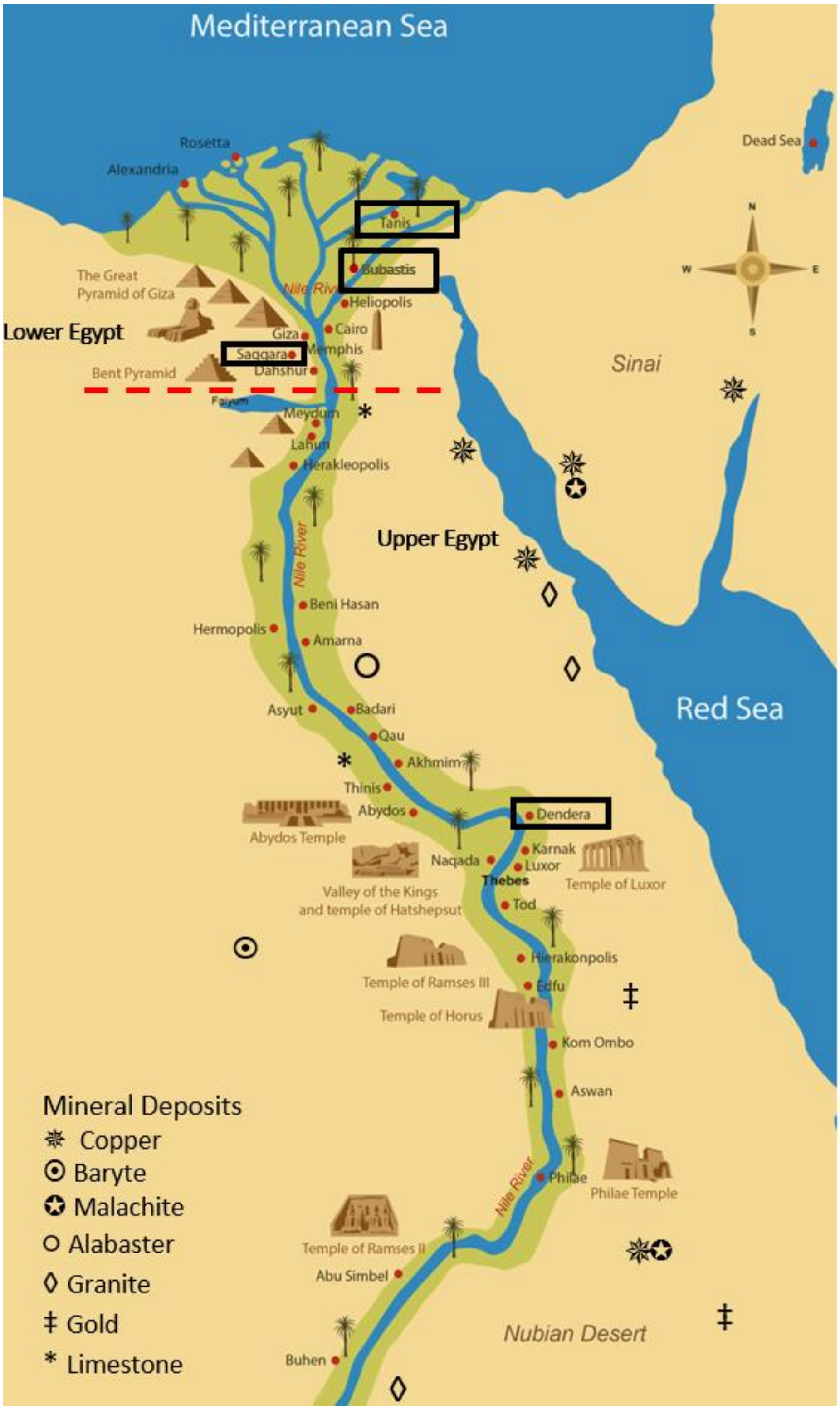


Figure 45. Map of Ancient Egypt.

Key cat cemeteries have been highlighted in black boxes. Mineral deposits have been illustrated also, using the key seen in the lower left.

Original: www.ancient-egypt-online.com, adapted by C. Raymond.

The mummified cat under investigation was re-wrapped towards the end of the Late Period, or the beginning of the Ptolemaic period, therefore it is important to consider where and how the remains were acquired. Between 350 - 200 BC, Egypt experienced its final years as a nation ruled by native Egyptians, as they were conquered by Alexander the Great in 332 BC, at which time, the capital moved from Sebenytos to Alexandria on the Mediterranean coast. At the close of the Late Period, interest in votive mummies begun to increase, perhaps as a result of the Egyptians finding that they could not trust the rulers. They may have turned to the gods directly, or in the face of increasing 'foreignness' from many different borders, they sought something more 'Egyptian' to bolster their nationalism (Wilson, 2010; Ikram, 2015). Wilson (2010) also speculates that the increased interest in votive mummies was a scheme conjured up to generate income for Egypt, after the downturn experienced during the Persian conquests. The motive remains unknown, while the result is undeniable, with such demand for these mummies, that the need could not be met. Perhaps this was the reason for the re-wrapping and 'recycling' of this mummy, as the demand could not be kept up. The reuse of already mummified animals would have reduced production time and lessened the resources needed, while still producing and supplying enough sacred votive offerings.

Further consideration could be given to the minerals used to make the pigment. The green pigment is made from a Cu-based mineral, and Cu mines were located in the Sinai region (Kohler, 2010), or in the Eastern desert (Shaw, 2000), from which copper ores and ingots were imported. Alabaster mines were located in Upper Egypt, close to Amarna (Figure 45). These minerals and many others were often mined for trade and art purposes, and then transported down river by boats (Aston, Harrelland and Shaw, 2000; McGrail, 2004; Ikram, 2009a). As a result, it is not possible to conclude that the mummy under review in this thesis was re-wrapped and decorated nearby to the mineral deposits bearing the utilised minerals, as transport of goods was well established up and down the river by this period, the Nile was the life source of Egypt and they relied on it heavily.

As previously mentioned, there were several animal cemeteries located across the expanse of Upper and Lower Egypt, and two major cat cemeteries are located at Bubastis and Tanis. These cities were political centres during the Third Intermediate Period, and therefore it could be suggested that the specimen IA.2402 originally came from one of these cemeteries. Alternatively, the animal cemetery at Saqqara is known for its tombs of mummified cats, and is in the Western Nile Delta. Having several cemeteries in such proximity to the city may have facilitated such reuse of animal remains for votive offerings during the Third Intermediate Period. However, this is a speculation, as there are no specific defining physical details on the specimen that may link it to a specific place. The mummy case study was brought back from Egypt circa 1858, by Sir Charles Nicholson, after his adventures in Egypt. Shortly after, in 1887-

89, the cemetery at Bubastis was excavated, uncovering 300,000 mummies, and cat mummies were removed en masse, shipped to the United Kingdom, and used as fertiliser (Morrison-Scott, 1951; Armitage and Clutton-Brock, 1981). The mummy is recorded in the Nicholson Museum catalogue of 1870, therefore, it would seem this mummy was not from the cemetery at Bubastis. According to a newspaper article in the Sydney Morning Herald about Sir Nicholson's adventures, he travelled from the Nile Delta region, through to Dendera, Karnak Temple, and Phylae (*The Sydney Morning Herald*, 1859). Throughout his journey he collected many artefacts, but there is no way of knowing if this mummy was personally excavated from a tomb, or purchased from hawkers, as was common practice as early as 1835 (Bell, 1989).

In collating this information regarding the political climate of Late Period and Ptolemaic Period Egypt, the locations of cat cemeteries and mineral deposits, the location of manufacture of this mummy is not clear. The fluidity of natural resources and commodities like copper or alabaster means that even if a mine site was close to a cemetery or city, it does not mean it was definitely from there. Similarly, the majority of cat cemeteries were located in the Nile Delta region, with a few located in Upper Egypt, and while the political centres remained mostly within the Delta after 1069 BC, the religious centres were always around Luxor and Karnak (Upper Egypt). This illustrates that mummies were being made across the country, in small villages with temples and in religious centres, not only in political centres. Additionally, in the 1850s, when Sir Charles Nicholson travelled to Egypt, the locals had already been removing mummified animals from tombs, specifically for sale to tourists. Thus, even if Nicholson had recorded that he acquired the animal in Dendera or Bubastis there is no guarantee that the animal was actually from that place. Unfortunately, the available evidence is insufficient, and the possibilities are too numerous to make a firm conclusion.

6 Conclusion

Overall, the results obtained through this research thesis have been enlightening of ancient Egyptian mummification procedures and associated practices. The findings made in this investigation can be summarised to a few key points:

1. Mummification techniques of padding, layering and wrapping were discovered using 3D imaging techniques;
2. Neutron CT was proven to be effective and non-destructive to the sample;
3. The partial contents of the mummy were non-destructively discovered, revealing two legs and a tail;
4. The animal was found to be a juvenile female cat of the species *Felis silvestris* through osteometric analysis of the CT reconstructions;
5. The remains were dated to 900-800 BC, while the wrapping was dated to 350-200BC, revealing a practice of recycling mummies in the ancient world to meet demands; and confirmed that the sample is an authentic original;
6. The pigments were made from natural minerals found within the bounds of Egypt's territory, specifically gypsum, Baryte, hematite and a Cu-mineral (yet to be identified).

3D reconstruction of the collected data from both X-ray and neutron CT allowed for an unprecedented view of the internal wrapping, layers and contents of the mummy. Both techniques revealed a partial skeleton, which, through detailed analysis and examination, allowed for identification of age at death and species of the remains. These techniques separately did address some of the main objectives if this study, however as a pair, they presented a complete and comprehensive view of the mummified animal. Imaging studies were non-destructive to the remains, and successfully illustrated their respective strengths and weaknesses. A main aim herein was to promote the use of neutron CT in future archaeometric studies, and show how it can add to the research prospects of the archaeological community. This was clearly demonstrated.

The acquisition of radiocarbon dates was successful in placing the mummy in its original time period. It also highlighted the discrepancy between ages of the remains to the wrappings, providing a first-hand example of how artefacts and mummified bundles were re-used to meet the increasing demands for votive offerings in the Late Period - Ptolemaic period. This difference in ages also prompted investigations into how remains from the Third Intermediate Period were obtained and re-wrapped in the Ptolemaic Period, making for an interesting back-story for the mummy.

Regarding pigment analysis, the variety of different scientific techniques used helped to inform about minerals used for funerary art in the ancient world. Each technique has proven to be useful and informative, some in more ways than one, demonstrating how applicable various techniques can be to aid in better understanding significant questions on mummification and votive offerings. It also demonstrated how scientific techniques, usually reserved for geological or chemical analysis can be applied in archaeological investigations. While the results gathered did not provide conclusive links to a particular burial ground or cemetery, they still provided valuable insight into pigment composition and practice. While inconclusive, knowing the general composition of the pigments allowed for ties to be made with the known ancient mineral mine locations, and further illustrating the extent of transporting goods up and down the Nile River.

It was desired in this thesis to discover the backstory, context and significance of this specific animal mummy. For the most part, these aims were met, except for confirming from where the mummy and materials originated. The mummy is heavily connected to the everyday practice of votive offering donation at temples, and the plight of everyday Egyptians. It demonstrates a popular cultural practice, that, during its re-wrapping, was at its peak popularity in Egyptian history. While still a unique sample, with its markings yet to be matched to a similar specimen, it was wrapped according to the period's common techniques, and is ~2600 years old, it is indisputably an authentic sample.

6.1 Future directions and investigations

There are a few questions that have either remained unanswered or have been posed as a result of the data collected that will need further investigations in the future. Primarily these have to do with analysis of the minerals and resins involved in the applied pigments. The relatively small quantity of colour agent (Cu) in the green pigment has made identification very difficult, and noise from the cellulose (textile) overshadows most spectra for these minerals. Similarly, resins have not been identified, most likely as they are organic and the databases in use are mostly for inorganic samples. To address this issue, analysis using Fourier transform infrared spectroscopy (FTIR) would be suggested, as it is more effective at identifying organic materials. This would assist to conclusive identify the Cu mineral used in the pigment, as well as identify the resin was used to bind the pigment to the wrapping. Another possible outcome would be to commence a long-term project to build up an online resource for the XRD and Raman spectra of ancient pigments. It would require investigation of a comprehensive collection of painted animal mummies and other artefacts, compilation of pigment standards and creation of a database. This would provide an invaluable resource to archaeologists carrying out these pigment studies.

Further investigations could be made of the amulet in the wrappings using X-ray CT. Primary scans revealed the artefact, but lacked fine detail. A higher resolution study of the object would be of interest to those who study amulets, and may provide more information about the origin of the mummy if said amulet was specific to a place or god. Similarly, the inner wrapping textile could be investigated further using higher resolution neutron CT, to study the weave technique, coarseness and direction. As the cat has been re-wrapped, it would be of interest to know if the inner textile is made differently to the outer textile, and whether it has been tampered with when the animal was re-wrapped.

A desire of the Australian Institute of Archaeology (AIA) is to create an interactive digital learning space associated with this mummy and other objects in its collection. The AIA has already taken 3D photogrammetry of the cat mummy, which will be combined with the X-ray and neutron CT data collected in this study. The reconstructions made from this data can and have been 3D printed for hands-on learning experiences, to make visualising the contents of the wrappings more tangible.

A long term, potential PhD project that would follow this case study would be to study a collection of cat mummies using neutron and X-ray CT, catalogue them and create an online database for studying votive mummies. As Ginsburg is a unique source when it comes to the wrapping of cat mummies, it would be good to see if the techniques he reported are common across the majority of cat mummies, or specific to Bubastis. This would allow for patterns in mummification technique and process to be recorded, and possibly matched to other samples. This may even allow for some unprovenanced mummies to be tentatively linked to burial sites and cemeteries, i.e. if Ginsburg's observations are specific to Bubastis, this mummy matches his observations, and its provenance has been found. To create a comprehensive and compelling case, a large number of mummies would need to be studied, and permission obtained from museums and curators. It is hoped that the use of neutron CT in this case study has been compelling and has addressed the concerns had by members the archaeological community, who have been apprehensive to undertake studies of this nature.

7 Reference List

Abdel-Maksoud, G. and El-Amin, A.-R. (2011) 'A Review on the Materials Used During The Mummification Processes in Antient Egypt', *Mediterranean Archaeology and Archaeometry*, 11(2), pp. 129–150.

Adams, J. (2015) 'Imaging animal mummies: history and techniques', in *Gifts for the Gods: ancient Egyptian animal mummies and the British*, pp. 68–71.

ANSTO (2014) *DINGO receives its operating licence*, *ANSTO Internal Media Centre*. Available at: http://www.ansto.gov.au/AboutANSTO/MediaCentre/News/ACS055501.

Armitage, P. L. and Clutton-Brock, J. (1981) 'A Radiological and Histological Investigation into the Mummification of Cats from Ancient Egypt', *Journal of Archaeological Science*, 8, pp. 185–196.

Aston, B., Harrelland, J. and Shaw, I. (2000) 'Stone', in Nicholson, P. T. and Shaw, I. (eds) *Ancient Egyptian Materials and Technology*. Cambridge: Cambridge University Press, pp. 5–77.

Baines, J. (1985) 'Color Terminology and Color Classification: Ancient Egyptian Color Terminology and Polychromy', *American Anthropologist*, 87, pp. 282–297.

Barnett, J. R., Miller, S. and Pearce, E. (2006) 'Colour and art: A brief history of pigments', *Optics and Laser Technology*, 38(4–6), pp. 445–453. doi: 10.1016/j.optlastec.2005.06.005.

Bell, P. (1989) *Sir Charles Nicholson: The First Patron, 'Sidere Mens Eadem Mutato': nineteenth-century art collections and architectural style at the University of Sydney*. Sydney University. Available at: http://hdl.handle.net/2123/397.

Bettuzzi, M., Casali, F., Morigi, M. P., Brancaccio, R., Carson, D., Chiari, G. and Maish, J. (2015) 'Computed tomography of a medium size Roman bronze statue of Cupid', *Applied Physics A: Materials Science and Processing*, 118(4), pp. 1161–1169. doi: 10.1007/s00339-014-8799-z.

Bewes, J. M., Morphett, A., Pate, F. D., Henneberg, M., Low, A. J., Kruse, L., Craig, B., Hindson, A. and Adams, E. (2016) 'Imaging ancient and mummified specimens: Dual-energy CT with effective atomic number imaging of two ancient Egyptian cat mummies', *Journal of Archaeological Science: Reports*. The Authors, 8, pp. 173–177. doi: 10.1016/j.jasrep.2016.06.009.

Bianchetti, P., Talarico, F., Vigliano, M. G. and Ali, M. F. (2000) 'Production and characterization of Egyptian blue and Egyptian green frit', *Journal of Cultural Heritage*, 1, pp. 179–188. doi: 10.1016/S1296-2074(00)00165-5.

Bleiberg, E., Barbash, Y. and Bruno, L. (2013) *Soulful Creatures: Animal Mummies in Ancient Egypt*. Brooklyn: GILES.

Brier, B. (2001) 'Case of the Dummy Mummy', *Archaeology*, 54(5), pp. 28–29.

Bücherl, T. (2017) *User facilities, International Society of Neutron Radiology (ISNR)*. Available at: https://www.isnr.de/index.php/facilities/user-facilities.

Burgio, L. and Clark, R. J. H. (2000) 'Comparative pigment analysis of six modern Egyptian papyri and an authentic one of the 13th century BC by Raman microscopy and other techniques', *Journal of Raman Spectroscopy*, 31(5), pp. 395–401.

Cavaleri, T., Buscaglia, P., Migliorini, S., Nervo, M., Piccablotto, G., Piccirillo, A., Pisani, M., Puglisi, D., Vaudan, D. and Zucco, M. (2017) 'Pictorial materials database: 1200 combinations of pigments, dyes, binders and varnishes designed as a tool for heritage science and conservation', *Applied Physics A: Materials Science and Processing*. Springer Berlin Heidelberg, 123(6), p. 419:1-15. doi: 10.1007/s00339-017-1031-1.

Chaplin, T. D., Clark, R. J. H. and Scott, D. A. (2006) 'Study by Raman microscopy of nine variants of the green-blue pigment verdigris', *Journal of Raman Spectroscopy*, 37(1–3), pp. 223–229. doi: 10.1002/jrs.1469.

Chen, Q., Wang, Q., Mitsumura, N. and Niida, H. (2013) 'Improved Cellulose by Ionic Liquid Mixture with Solid Acid Catalysis and Its Application in Polyethylene Glycol Liquefcation', *Materials Sciences and Applications*, 4(12), pp. 839–845.

Cierniak, R. (2011) 'Some words about the history of computed tomography', in *X-Ray Computed Tomography in Biomedical Engineering*, pp. 1–319. doi: 10.1007/978-0-85729-027-4.

Clark, K. A., Ikram, S. and Evershed, R. P. (2013) 'Organic chemistry of balms used in the preparation of pharaonic meat mummies.', *Proceedings of the National Academy of Sciences of the United States of America*, 110(51), pp. 20392–5. doi: 10.1073/pnas.1315160110.

Clark, R. J. H. (2002) 'Pigment identification by spectroscopic means: an arts/science interface', *Comptes Rendus Chimie*, 5(1), pp. 7–20. doi: 10.1016/S1631-0748(02)01341-3.

Cornelius, I., Swanepoel, L. C., Plessis, A. Du and Slabbert, R. (2012) 'Looking inside votive creatures: computed tomography (CT) scanning of ancient Egyptian mummified animals in Iziko museums of South Africa: A preliminary report', *Akroterion*, 57, pp. 129–148.

David, A. (1997) 'Disease in Egyptian mummies : the contribution of new technologies', *The Lancet*, 349, pp. 1760–63.

David, R., Edwards, H. G. M., Farwell, D. W. and De Faria, D. L. A. (2001) 'Raman spectroscopic analysis of ancient Egyptian pigments', *Archaeometry*, 43(4), pp. 461–473. doi: 10.1111/1475-4754.00029.

Deer, W. (1998) *Rock-forming Minerals: Non-Silicates, VOlume 5B*. Edited by L. L. Chang, R. Howie, and J. Zussman. London: Geological Society of London.

Dodson, A. (2005) 'Bull Cults', in Ikram, S. (ed.) *Divine Creatures: Animal Mummies in Ancient Egypt.* New York: The American University in Cairo Press, pp. 72–105.

Edwards, H. G. M. and Ali, E. M. A. (2011) 'Raman spectroscopy of archaeological and ancient resins: Problems with database construction for applications in conservation and historical provenancing', *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy*. Elsevier B.V., 80(1), pp. 49–54. doi: 10.1016/j.saa.2011.01.030.

Ejsmond, W. and Przewlocki, L. (2014) 'Some Remarks on Cat Mummies in Light of the Examination of Artefacts from The National Museum in Warsaw Collection``', *Studies in Ancient Art and Civilisation*. Edited by J. Debowska-Ludwin, M. A. Jucha, and P. Kolodziejczyk, 18, pp. 239–258.

Feisner, E. A. and Reed, R. (2013) *Color Studies*. New York: Fairchild Books.

Fritzsche, H., Huot, J. and Fruchart, D. (2016) *Neutron Scattering and Other Neutron Techniques for Hydrogen in Materials*. Springer.

Ginsburg, L. (1999) 'Les chats momifiés de Bubasteion de Saqqarah.', *Annales du Service des Antiquités de l'Égypte*, 74, pp. 183–191.

Gliddon, G. (2008) *Otia Aegyptiaca: Discourses on Egyptian archaeology and hiroglyphical discoveries*. London: J. Madden.

Grifa, C., Cavassa, L., De Bonis, A., Germinario, C., Guarion, V., Izzo, F., Kakoulli, I., Langella, A., Mercurio, M. and Morra, V. (2016) 'Beyond Vitruvius: New Insight in the Technology of Egyptian Blue and Green Frits', *Journal of the American Ceramic Society*, 99(10), pp. 3467–3475. doi: 10.1111/jace.14370.

Habermehl, K. H. (1980) *Altersbestimmung bei Versuchstieren*. Berlin & Hamburg: Verlag Paul Parey.

Habermehl, K. H. (1985) *Altersbestimmung bei Wild- und Pelztieren*. Berlin & Hamburg: Verlag Paul Parey.

Harrell, J. A. and Lewan, M. D. (2002) 'Sources of Mummy Bitumen in Ancient Egypt and Palestine', *Archaeometry*, 44(2), pp. 285–293.

Hartley, M., Buck, A. and Binder, S. (2011) 'Canine Interments in the Teti Cemetary North at Saqqara during the Graeco-Roman period', in *Abusir and Saqqara in the Year 2010/1*. Prague: Czech Institute of Egyptology, Charles University, pp. 17–29.

Harwood-Nash, D. C. (1979) 'Computed Tomography of Ancient Egyptian Mummies', *Journal of Computer Assisted Tomography*, 3, pp. 768–773.

Hope, G. A., Buckley, A. N., Parker, G. K., Numprasanthai, A., Woods, R. and Mclean, J. (2012) 'The interaction of n-octanohydroxamate with chrysocolla and oxide copper surfaces', *Minerals Engineering*. Elsevier Ltd, 36–38, pp. 2–11. doi: 10.1016/j.mineng.2012.01.013.

Ikram, S. (2005) 'The Loved Ones : Egyptian Animal Mummies as Cultural and Environmental Indicators', in *Proceedings of the Sixth International Symposium on the Archaeozoology of Southwestern Asia and Adjacent Areas*, pp. 240–248.

Ikram, S. (2009a) *Ancient Egypt: An Introduction*. Cambridge: Cambridge University Press.

Ikram, S. (2009b) 'Mummification', *Encyclopedia of Egyptology*.

Ikram, S. (2011) 'Experimental Archaeology: from Meadow to Em-Baa-Lming Table', in Grave-Browns, C. (ed.) *Experiment and Experience*. Cardiff: University of Wales Press, pp. 53–74.

Ikram, S. (2015) *Divine Creatures*. Cairo: AUC Press.

Ikram, S. and Dodson, A. (1988) *The Mummy in Ancient Egypt: Equipping the Dead for Eternity*. London: Thames and Hudson.

Ikram, S. and McKnight, L. M. (2015) '70 million animal mummies: Egypt's dark secret'. United Kingdom: BBC Horizon.

Isherwood, I., Jarvis, H. and Fawcitt, R. (1979) 'Radiology of the Manchester mummies', in *A.R.David(ed),The Manchester Mummy Project: Multidisciplinary Research on Ancient Egyptian Mummified Remains.*, pp. 25–64.

Janssens, K. and Van Grieken, R. (2004) *Non-destructive Micro Analysis of Cultural Heritage*

Materials. Antwerp: Wilson and Wilson.

Johansson, C., Metz, G. and Ulhorn, M. (2015) ‘Feline Descendant of the Red or the Black land: A Multidisciplinary Investigation of an Unusually Large Ancient Egyptian Cat Mummy’, in *Egyptian Bioarchaeology*, pp. 177–200.

Katsaros, T. and Liritzis, I. (2011) ‘Identification of Theophrastus’ pigments egyptios kyanos and psimythion from archaeological excavations’, *ArchéoSciences*, 34(1), pp. 69–80. doi: 10.4000/archeosciences.2632.

Kemp, B. (2006) *Ancient Egypt: Anatomy of a Civilisation*. 2nd edn. Oxon: Routledge.

Kohler, E. C. (2010) ‘Theories of State Formation’, in Wendrich, W. (ed.) *Egyptian Archaeology*. West Sussex: Wiley-Blackwell, pp. 36–54.

Kretschmer, W., Grundherr, K. Von, Kritzler, K., Morgenroth, G., Scharf, A. and Uhl, T. (2004) ‘The mystery of the Persian mummy: original or fake ?’, *Nuclear Instruments and Methods in Physics Research B*, 223–224, pp. 672–675. doi: 10.1016/j.nimb.2004.04.124.

Kurushima, J. D., Ikram, S., Knudsen, J., Bleiberg, E., Grahn, R. A. and Lyons, L. A. (2012) ‘Cats of the pharaohs : genetic comparison of Egyptian cat mummies to their feline contemporaries’, *Journal of Archaeological Science*. Elsevier Ltd, 39(10), pp. 3217–3223. doi: 10.1016/j.jas.2012.05.005.

Lafuente, B., Downs, R. T., Yang, H. and Stone, N. (2015) ‘The power of databases: the RRUFF project’, in Armbruster, T. and Danisi, R. (eds) *Highlights in Mineralogical Crystallography*. Berlin: W. De Gruyter, pp. 1–30.

Lehmann, E. H., Hartmann, S. and Speidel, M. O. (2010) ‘Investigation of the content of ancient Tibetan metallic Buddha statues by means of neutron imaging methods’, *Archaeometry*, 52(3), pp. 416–428.

Linseele, V., Van Neer, W. and Hendrickx, S. (2007) ‘Evidence for early cat taming in Egypt’, *Journal of Archaeological Science*, 34, pp. 2081–2090. doi: 10.1016/j.jas.2008.04.009.

Linseele, V., Van Neer, W. and Hendrickx, S. (2008) ‘Early cat taming in Egypt: a correction’, *Journal of Archaeological Science*, 35(9), pp. 2672–2673. doi: 10.1016/j.jas.2008.04.009.

Lloyd, A. B. (2000a) ‘The Late Period’, in Shaw, I. (ed.) *The Oxford History of Ancient Egypt*. Oxford: Oxford University Press, pp. 364–387.

Lloyd, A. B. (2000b) ‘The Ptolemaic Period’, in Shaw, I. (ed.) *The Oxford History of Ancient Egypt*. Oxford: Oxford University Press, pp. 388–413.

Malek, J. (1993) *The Cat in Ancient Egypt*. London: British Museum Press.

Malgora, S., Borgonovo, S., Moioli, M., Di Giancamillo, A., Domeneghini, C. and Di Giancamillo, M. (2011) ‘Investigation of the Trento Cat Mummy’, *Journal of Biological Research*, 84(1), pp. 354–358.

Mannes, D., Schmid, F., Frey, J., Schmidt-Ott, K. and Lehmann, E. (2015) ‘Combined Neutron and X-ray imaging for non-invasive investigations of cultural heritage objects’, *Physics Procedia*, 69, pp. 653–660.

Marey Mahmoud, H., Kantiranis, N., Ali, M. and Stratis, J. (2011) ‘Characterization of ancient

Egyptian wall paintings, the excavations of Cairo University at Saqqara', *International journal of conservation science*, 2(3), pp. 145–154.

Maurer, J., Mohring, T. and Rullkötter, J. (2002) 'Plant Lipids and Fossil Hydrocarbons in Embalming Material of Roman Period Mummies from the Dakhleh Oasis, Western Desert, Egypt.', *Journal of Archaeological Science*, 29, pp. 751–762. doi: 10.1006/jasc.2001.0773.

Mays, C., Cantrill, D. J., Stilwell, J. D. and Bevitt, J. J. (2017) 'Neutron tomography of Austrosequoia novae-zeelandia e comb. nov. (Late Cretaceous, Chatham Islands, New Zealand): implications for Sequoioideae phylogeny and biogeography', *Early Journal of Systematic Palaeontology*. Taylor & Francis, pp. 1–20. doi: 10.1080/14772019.2017.1314898.

McGrail, S. (2004) *Boats of the World: From the Stone Age to Medieval Times*. Oxford: Oxford University Press.

Mcknight, L. M. (2015) 'What lies beneath: imaging animal mummies', in *Gifts for the Gods: ancient Egyptian animal mummies and the British*, pp. 72–82.

Morrison-Scott, T. C. (1951) 'The mummified cats of ancient Egypt', pp. 861–867.

Van Neer, W., Linseele, V. and Friedman, R. (2004) 'Animal burials and food offerings at the elite cemetery hk6 of Hierakonpolis', in Hendrickx, S. and Adams, B. (eds) *Egypt at Its Origins: Studies in Memory of Barbara Adams: Proceedings of the International Conference 'Origin of the State, Predynastic and Early Dynastic Egypt'*. Krakow: Peeters Publishers, p. 1142.

Van Neer, W., Linseele, V., Friedman, R. and De Cupere, B. (2014) 'More evidence for cat taming at the Predynastic elite cemetery of Hierakonpolis (Upper Egypt)', *Journal of Archaeological Science*. Elsevier Ltd, 45(1), pp. 103–111. doi: 10.1016/j.jas.2014.02.014.

Nguyen, H.-Y. (2011) *Computed Tomography for the Non-Destructive Imaging of Cultural Heritage: X-Ray, Gamma and Neutron Sources*.

Nicholson, P. T., Ikram, S. and Mills, S. (2015) 'The Catacombs of Anubis at North Saqqara', *Antiquity*, 89(345), pp. 645–661. doi: 10.15184/aqy.2014.53.

Ottoni, C., Van Neer, W., De Cupere, B., Daligault, J., Guimaraes, S., Peters, J., Spassov, N., Prendergast, M. E., Boivin, N., Morales-Muñiz, A., Bălăşescu, A., Becker, C., Benecke, N., Boroneant, A., Buitenhuis, H., Chahoud, J., Crowther, A., Llorente, L., Manaseryan, N., Monchot, H., Onar, V., Osypińska, M., Putelat, O., Quintana Morales, E. M., Studer, J., Wierer, U., Decorte, R., Grange, T. and Geigl, E.-M. (2017) 'The palaeogenetics of cat dispersal in the ancient world', *Nature Ecology & Evolution*, 1(7), p. 139. doi: 10.1038/s41559-017-0139.

Pagès-Camagna, S. and Colinart, S. (2003) 'the Egyptian Green Pigment : Its Manufacturing Process and Links To Egyptian Blue*', *Archaeometry*, 4, pp. 637–658.

Pagès-Camagna, S., Reiche, I., Brouder, C., Cabaret, D., Rossano, S., Kanngießer, B. and Erko, A. (2006) 'New insights into the colour origin of archaeological Egyptian blue and green by XAFS at the Cu K-edge', *X-Ray Spectrometry*, 35(2), pp. 141–145. doi: 10.1002/xrs.885.

Petaros, A., Jankovic, I., Cavalli, F., Ivanac, G., Brkljacic, B. and Cavka, M. (2015) 'Mummified remains from the Archaeological Museum in Zagreb, Croatia - Reviewing peculiarities and limitations of human and non-human radiological identification and analysis in mummified remains', *Journal of Forensic and Legal Medicine*, 35(2015), pp. 54–61. doi: 10.1016/j.jflm.2015.07.002.

Petrie, F. (2016) *Amulets*. Read Books Ltd.

van der Plaats, G. and Vilibrief, P. (2012) *Medical X-Ray Techniques in Diagnostic Radiology: A textbook for radiographers and Radiological Technicians*. Springer Science and Business Media.

Plessis, A. Du, Slabbert, R., Swanepoel, L. C., Els, J., Booysen, G. J., Ikram, S. and Cornelius, I. (2015) 'Three-dimensional model of an ancient Egyptian falcon mummy skeleton', *Rapid Prototyping Journal*, 21(4), pp. 368–372. doi: 10.1108/RPJ-09-2013-0089.

Prudencio, M. I., Marques, J. G., Pereira, M. A. S., Santos, J. P. P., Burbidge, C. I. I., and Dias, M. I. I. (2013) 'Neutron imaging techniques applied to studies in the archaeological and cultural heritage fields', *Mediterraneann Archaeology and Archaeometry*, 13(3), pp. 137–143.

Ragai, J. (1986) 'Colour: its significance and production in Ancient Egypt', *Endeavour*, 10(2), pp. 74–79. doi: 10.1016/0160-9327(86)90134-1.

Rapp, G. (2009) *Archaeomineralogy: Natural Science in Archaeology*. 2nd edn. Heidleberg: Springer Science and Business Media.

Remler, P. (2010) *Egyptian Mythology, A to Z*. Infobase Publishing.

Robins, G. (2008) *The Art of Ancient Egypt*. Harvard University Press.

Salvemini, F., Bevitt, J., Liss, K. D. and Garbe, U. (2016) 'DINGO – the neutron imaging station at ANSTO: embracing material science, palaeontology, and cultural heritage', *Neutron News*, 27(2). doi: 10.1080/10448632.2016.1163982.

Shaw, I. (2000) 'Egypt and the Outside World', in Shaw, I. (ed.) *The Oxford History of Ancient Egypt*. Oxford: Oxford University Press, pp. 308–323.

Shaw, I. (2004) *Ancient Egypt: A Very Short Introduction*. Oxford: Oxford University Press.

Smith, G. D. and Clark, R. J. H. (2004) 'Raman microscopy in archaeological science', *Journal of Archaeological Science*, 31(8), pp. 1137–1160. doi: 10.1016/j.jas.2004.02.008.

Smith, S. T. (2016) 'Unwrapping the Mummy: Hollywood Fantasies, Egyptian Realities', in Schablitsky, J. M. (ed.) *Box Office Archaeology: Refining Hollywood's Portrayals of the Past.* Routledge, p. 256.

Di Stefano, L. M. and Fuchs, R. (2011) 'Characterisation of the pigments in a Ptolemaic Egyptian Book of the Dead papyrus', *Archaeological and Anthropological Sciences*, 3(3), pp. 229–244. doi: 10.1007/s12520-011-0054-3.

Susarla, S. M., Mulliken, J. B., Kaban, L. B., Manson, P. N. and Dodson, T. B. (2017) 'The colourful history of malachite green: from ancient Egypt to modern surgery', *International Journal of Oral and Maxillofacial Surgery*. International Association of Oral and Maxillofacial Surgeons, 46(3), pp. 401–403. doi: 10.1016/j.ijom.2016.09.022.

Taylor, J. (2000) 'The Third Intermediate Period', in Shaw, I. (ed.) *The Oxford History of Ancient Egypt*. Oxford: Oxford University Press, pp. 324–363.

The Sydney Morning Herald (1859) 'Second Lecture of Sir Charles Nicholson upon Ancient Egypt', October, p. 4.

Wasef, S., Wood, R., Merghani, S. El, Ikram, S., Curtis, C., Holland, B., Willerslev, E., Millar, C. D. and Lambert, D. M. (2015) 'Radiocarbon dating of Sacred Ibis mummies from ancient Egypt', *Journal of Archaeological Science: Reports*. Elsevier B.V., 4, pp. 355–361. doi: 10.1016/j.jasrep.2015.09.020.

Wilson, P. (2010) 'Consolidation, Innovation and Renaissance', in Wendrich, W. (ed.) *Egyptian Archaeology*. West Sussex: Wiley-Blackwell, pp. 241–258.

Zivie, A. and Lichtenberg, R. (2015) 'The Cats of the Goddess Bastet', in Ikram, S. (ed.) *Divine Creatures: Animal Mummies in Ancient Egypt.* Cairo: American University in Cairo Press, pp. 106–119.

8 Appendix

Appendix 1. Felis silvestris and Felis chaus

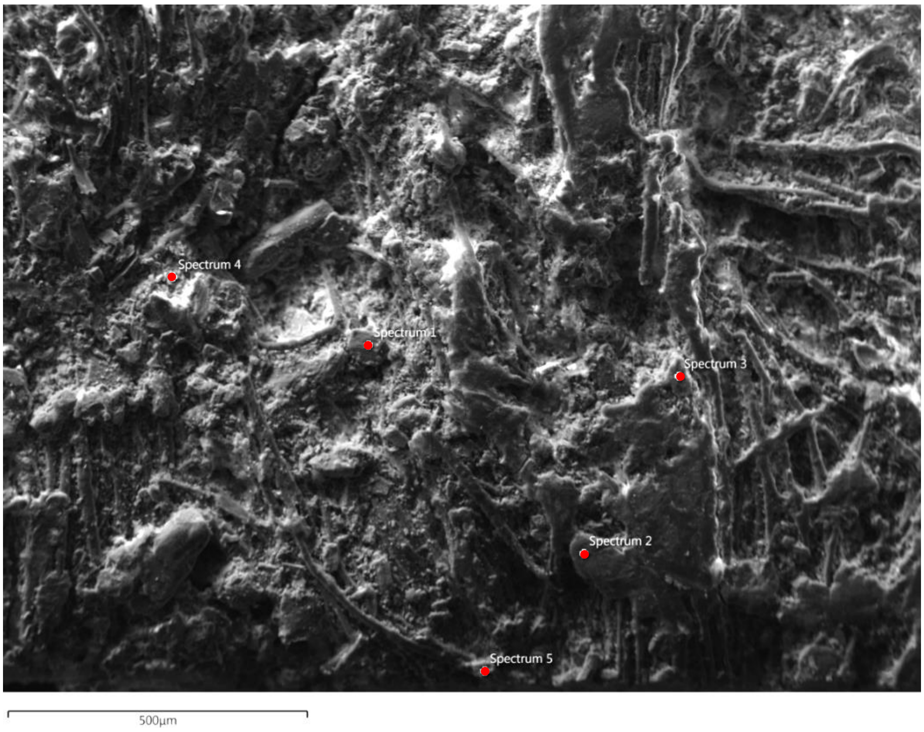

Felis silvestris ©Arnaud Quanjer Photography (left);
Felis chaus ©Anup Shah, Arkive (right).

Appendix 2. Sample information

Samples	Details	Purpose	Techniques to be applied
A	Animal Mummy	Age, mummification	X-ray/Neutron CT
B	Green Pigment on Textile		
B1	Fragment of B	Pigment analysis	SEM/Raman
B2	Fragment of B	Pigment analysis	XRD
C	Red Pigment on Textile		
C1	Fragment of C	Pigment analysis	SEM/Raman
C2	Fragment of C	Pigment analysis	XRD
D	Threads of Mummy Wrapping	Radiocarbon dating	C14 Dating *
E	Fur and Skin Fragment		
E1	Fragment of E	Speciation	Protein analysis *
E2	Remainder of E	Radiocarbon dating	C14 Dating *

List of samples, purpose of the acquisition and techniques to be applied.
** Indicates a destructive investigative technique.*

Appendix 3. Additional EDS data on red pigment

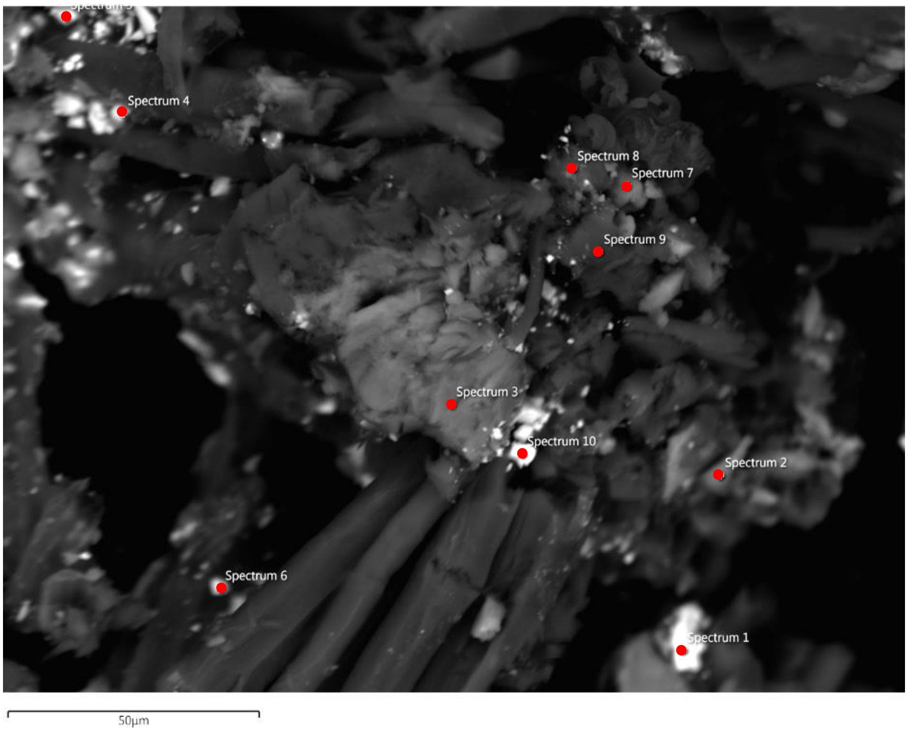


Locations of spot analysis on red pigment sample (*C1*), marked with red dots. The objective was to locate areas of high Fe. *Corresponding results in table 2.*

Red spot analysis EDS results					
	1	**2**	**3**	**4**	**5**
O	56.08	48.12	38.17	15.1	13.19
Na	-	-	-	1.09	0.68
Mg	-	-	2.25	0.61	0.41
Al	-	0.15	2.29	0.78	1.66
Si	-	0.27	4.56	15.61	2.07
P	-	-	-	-	0.11
S	19.51	22.24	15.7	4.78	1.1
Cl	-	-	0.68	0.5	0.13
K	-	-	0.44	0.6	0.2
Ca	24.19	29.05	19.51	6.31	1.21
Ti	-	-	-	-	0.1
Fe	0.22	0.17	16.39	47.36	78.58
Cu	-	-	-	-	0.37
Zn	-	-	-	7.25	-
Total Wt%	**100**	**100**	**99.99**	**99.99**	**99.81**

Spot analysis results for red pigment (normalised). High oxygen readings are a result of the uneven nature of the textile sample.

Appendix 4. Additional EDS data on green pigment



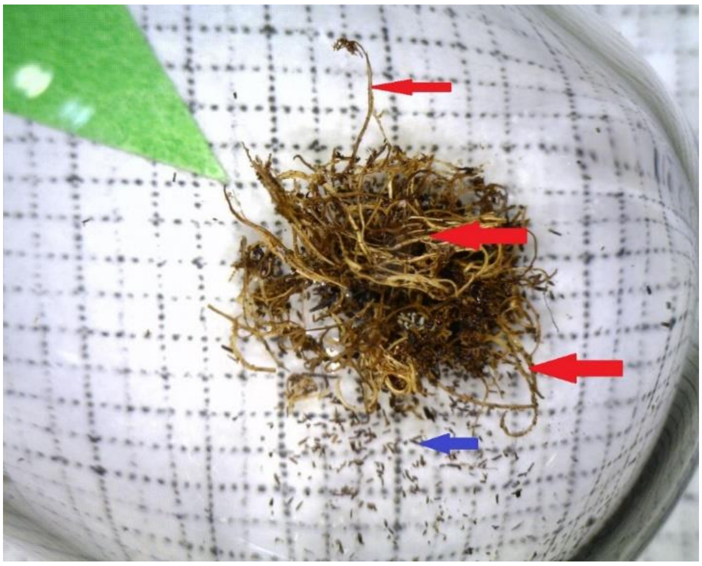
Locations of spot analysis on *B1*, marked in red. The objective was to located Cu bearing fragments to determine origin of green colour. *Corresponding results in table 3.*

	<u>Green spot analysis EDS results</u>									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
O	9.09	63.5	53.4	21.9	14	32.7	40.5	59.3	45.1	2.66
Na	-	1.01	0.87	0.37	0.4	1.75	0.28	6.81	1.99	-
Mg	-	0.54	-	0.53	0.33	0.94	0.85	2.47	0.99	-
Al	0.34	0.92	3.66	0.9	0.53	1.18	16.9	1.3	1.15	0.08
Si	1.05	3.58	4.17	3.31	1.26	4.97	29.4	2.48	2.81	0.42
P	-	-	-	0.24	0.33	-	0.25	0.25	12.3	-
S	0.8	2.2	2.05	8.24	3.04	5.94	0.75	3.19	-	10.4
Cl	0.67	1.65	1.51	10.9	7.23	15.5	0.56	10.7	7.88	0.35
K	0.31	0.66	-	2.29	1.86	3.22	1.65	1.93	1.98	-
Ca	1.15	9.85	3.44	4.91	3.38	7.66	0.55	3.54	18.6	-
Ti	-	-	-	-	-	-	0.28	-	-	-
Cr	-	-	-	-	1.45	-	-	-	-	-
Fe	-	8.28	13	1.31	2.14	2.91	7.38	0.99	1.22	-
Cu	2.99	3.81	8.3	0.53	1.9	1.18	0.19	0.62	0.86	0.4
Zn	-	-	-	-	-	-	-	-	-	-
Sr	0.07	-	-	-	-	-	-	-	-	0.87
Ba	83.5	3.96	9.6	41.7	42.4	21.1	0.2	5.44	5.1	84.2

W	-	-	-	0.88	-	-	0.27	-	-	-
Au	-	-	-	-	-	-	-	-	-	0.58
Pb	-	-	-	1.98	19.8	-	-	1.06	-	-
Total Wt%	**99.97**	**99.96**	**100**	**99.99**	**100.05**	**99.05**	**100.01**	**100.08**	**99.98**	**99.96**

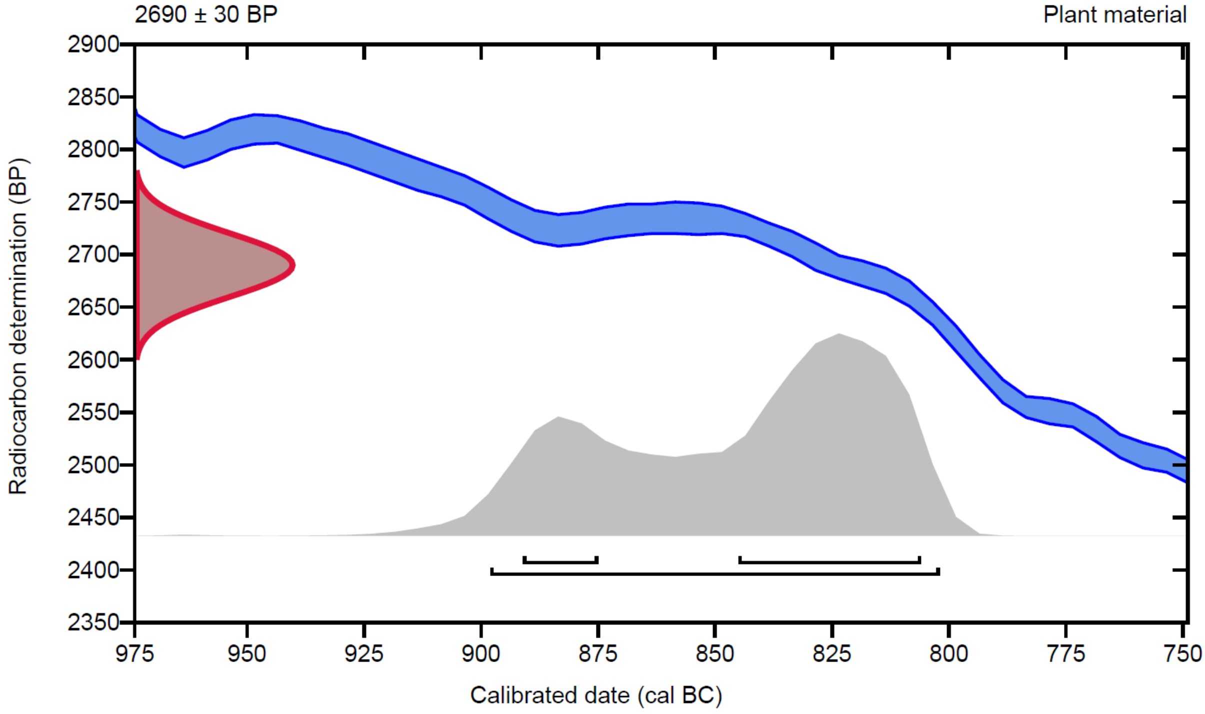
Spot analysis results for green pigment (normalised). High oxygen readings are a result of the uneven nature of the textile sample.

Appendix 5. Accelerator mass spectrometry sample pre-treatment

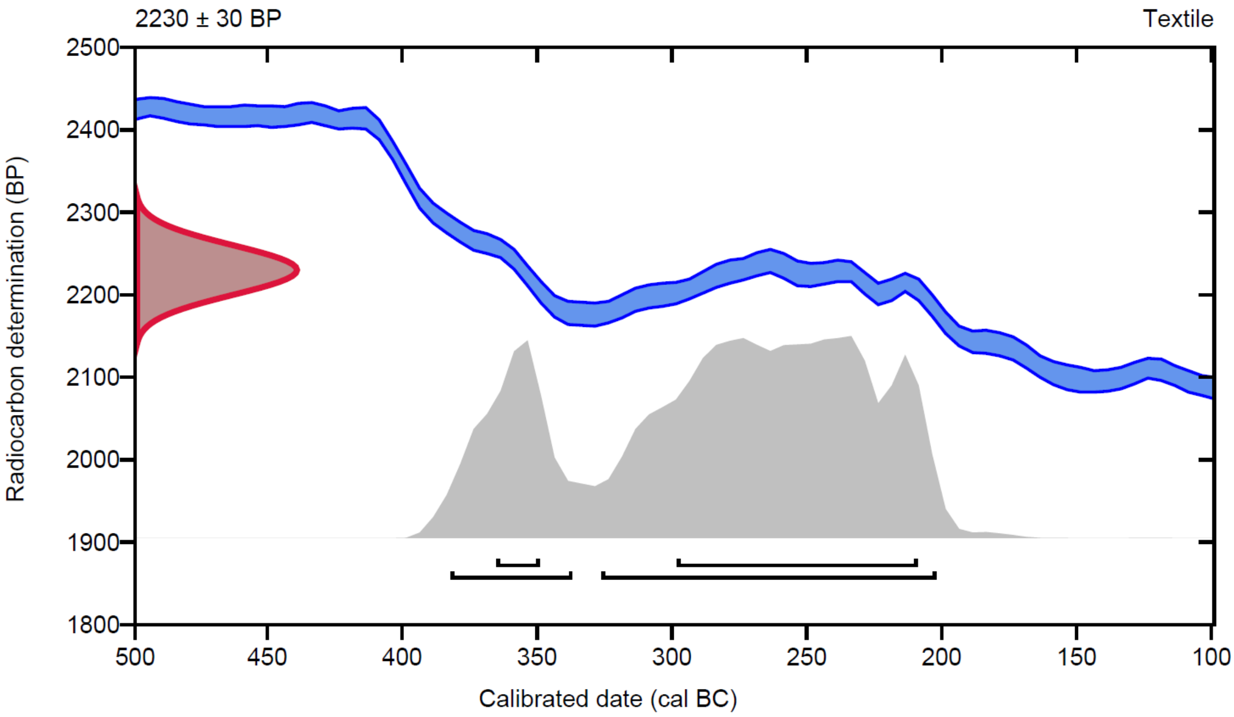


Fur sample (*Beta-473336*) after pre-treatment; Fur has broken down into smaller particles (blue arrow), and majority of sample is plant material (red arrows).

Appendix 6. Radiocarbon date results

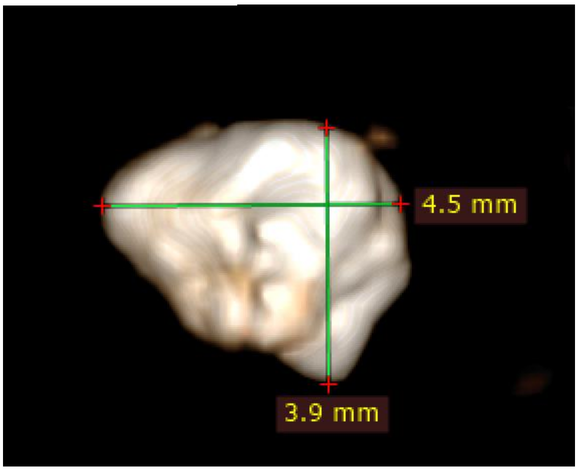


Radiocarbon dating results for fur and plant material sample (sample taken from inside wrapping).



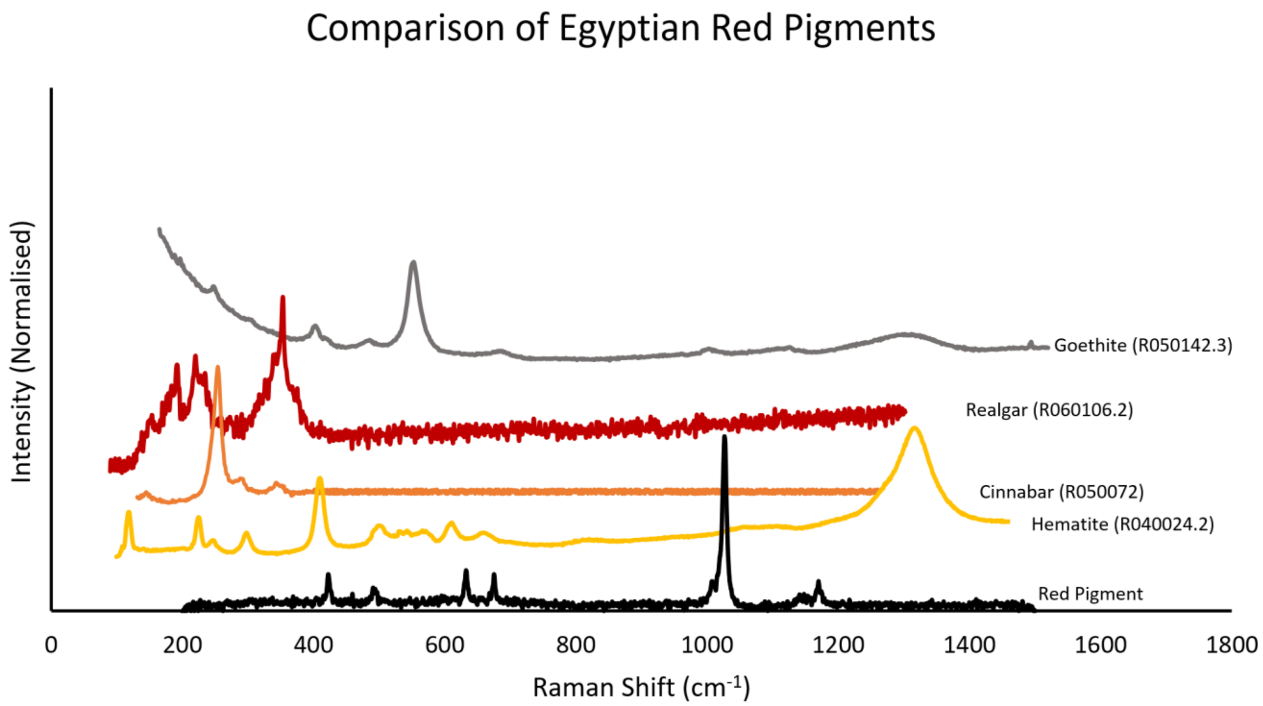
Radiocarbon dating results for textile sample (taken from external most wrapping).

Appendix 7. 3D Amulet reconstruction

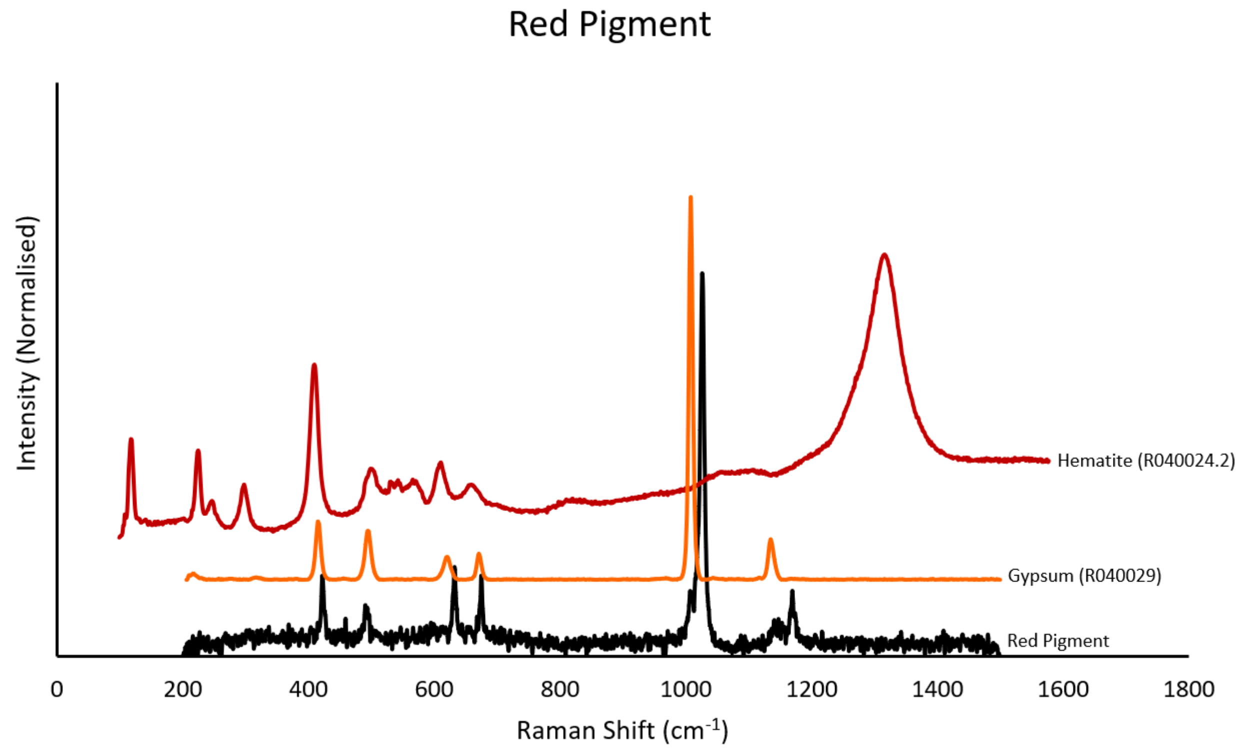


Amulet reconstructed in X-ray CT, showing measurements and lack of discernible shape.

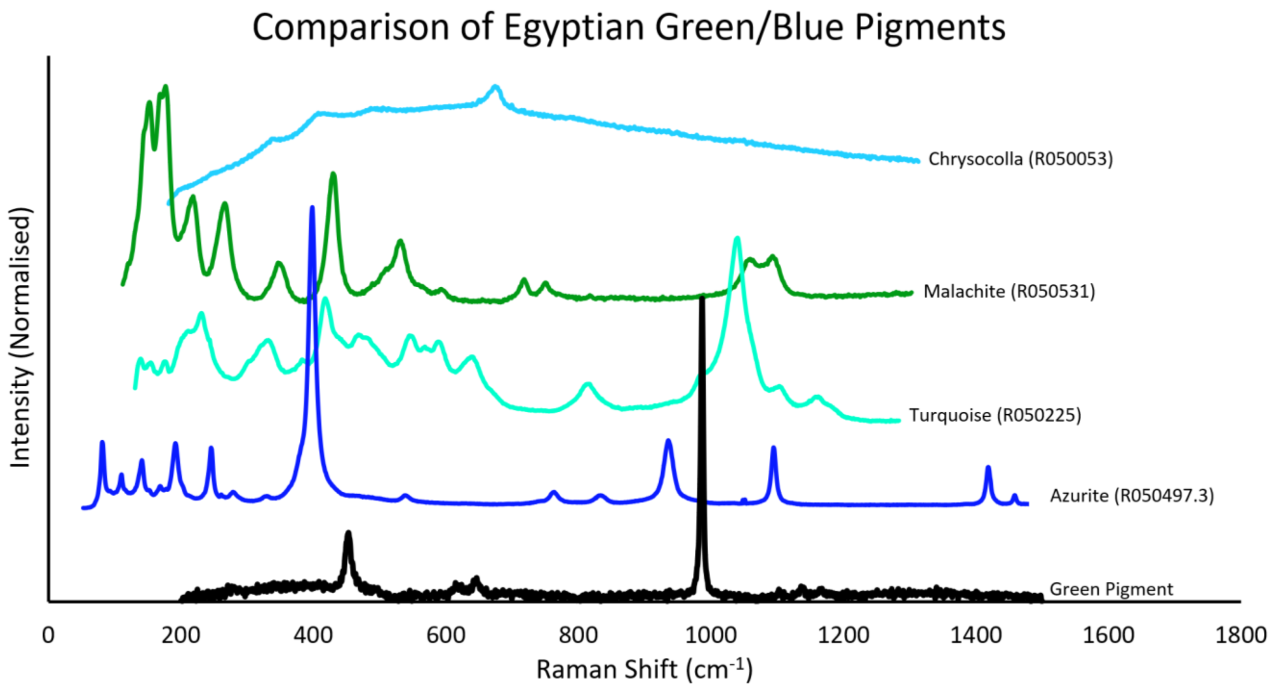
Appendix 8. Additional Raman Spectra comparisons



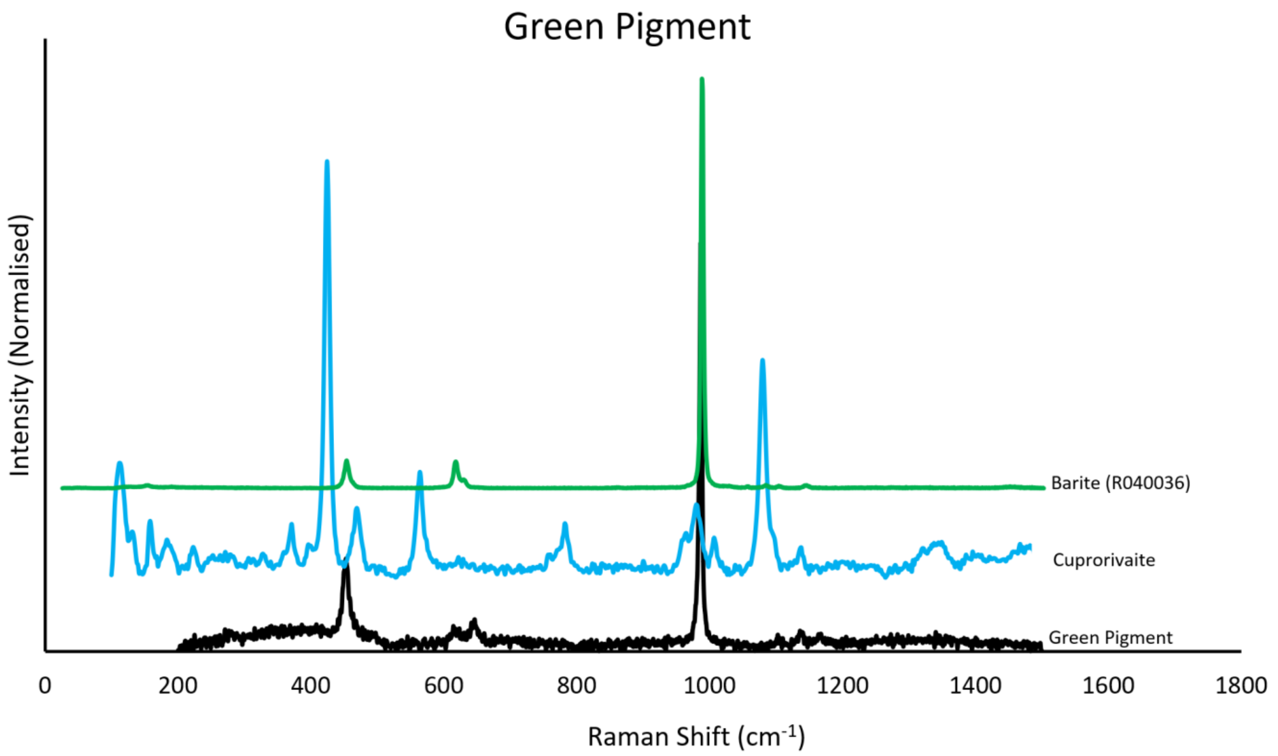
8. 1. Comparisons of red pigments present in ancient Egypt to red pigment results (black). *Numbers in brackets refer to mineral code in RRUFF database (www.rruff.info). Normalised, and offset for display: goethite +1, realgar +0.8, cinnabar +0.4, hematite +0.05.*



8. 2. Red pigment results compared to gypsum and hematite show likely components of coloured pigment, however the shift in peak between gypsum and the red pigment is not identified. *Numbers in brackets refer to mineral code in RRUFF database (www.rruff.info). Normalised, and offset for display: hematite +0.05, gypsum +0.2.*



8. 3. Comparisons of green pigments present in ancient Egypt to green pigment results (black). *Numbers in brackets refer to mineral code in RRUFF database (www.rruff.info). Normalised, and offset for display: chrysocolla +0.7, malachite +0.7, Turquoise +0.2, Azurite +0.3.*



8. 4. Green pigment results compared to baryte and cuprorivaite show some clear correlations, and some peaks remain unidentified. *Numbers in brackets refer to mineral code in RRUFF database (www.rruff.info). Normalised, and offset for display: baryte +1, cuprorivaite +0.3.*