

# THE DAMA DE ELCHE



*The Dama de Elche (May 2003 AD)*



*The Dama de Elche (circa 4th century BC)*

Between March and May 2003 Factum Arte carried out all work relating to the production of the highest resolution facsimile ever attempted of an important, complex sculpture, The Dama De Elche.

All work was carried out with the full support of the Museo Arqueológico Nacional (Madrid) and Museo Arqueológico (Alicante). The project was commissioned by Diputación Provincial de Alicante and funded by the Caja de Ahorros del Mediterráneo and the Universidad Miguel Hernández (Elche)

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# CONTENTS

PREFACE	9
INTRODUCTION	11
Why Use Digital Technology?	12
THE USE OF REPLICAS IN HERITAGE	13
Initial Research	14
THE DAMA DE ELCHE	15
Brief History	15
The Condition of the Sculpture	16
GATHERING THE DIGITAL DATA	19
Laser Scanning	20
Scanning the Overall Shape	21
Scanning the Surface Details	23
Documentation	24
PRODUCTION	25
Sourcing and Testing of Materials	25
3D Printing	26
Facsimile Version One:	27
Facsimile Version Two:	28
Routed Sections	28
Assembling and Casting the Model	29
CONCLUSION	31



## APPENDIX

FACTUM ARTE	35
TECHNICAL DETAILS	37
Scanning Using Factum Arte's Seti Scanner	37
Scanning Using the Minolta Laser Scanner	38
Scanning Using 3D Scanners' ModelMaker W	39
Z Corp 3D Printing	40
Routing	37
The Cutting Strategy	41
Documentation	42
PLATES	

## PREFACE

The work carried out by Factum Arte on The Dama De Elche is the first high resolution 3D scanning of any object in a major collection in Spain. The aim was to carry out all scanning and documentation work at the highest resolution in order to produce the most accurate facsimile possible and demonstrate the role that new technologies can play in the documentation, monitoring, study and display of objects in museum collections.

Many of the technical innovations made by Factum Arte over the past two years have had a direct impact on the working methods used to produce the facsimile of The Dama de Elche. However, these technologies continue to be perfected and direct comparisons between different scanning methods, methods of 3D output, and fabrication techniques have also been undertaken. This work is essential to encourage debate and develop a practical and scientific approach to the use and applications of laser scanning and facsimile production. There are many claims made by the different companies marketing the technologies used in this work, most of which have been developed for different applications, and it has become clear that there is a universal need in the heritage sector for a clearer understanding of the practical constraints when the technologies are applied to museum objects.

All the work detailed in this book was carried out between the beginning of March and the end of May 2003. Many more months of work are required to analyse the results, carry out further tests and present all the research in a form that will be of use for the practical conservation of important works like The Dama De Elche.

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Director, Factum Arte

## INTRODUCTION



In November 2002, Factum Arte was approached by the Diputación Provincial de Alicante to make a high resolution replica of The Dama de Elche for the Museo Arqueológico (MARQ). The replica will be the centre piece of an exhibition at the Museo MARQ which describes the technology and processes involved in its production. With the full support of the Museo Arqueológico Nacional, where the sculpture is now shown, Factum Arte carried out digital 3D documentation of The Dama de Elche – the first time such documentation has been carried out on any object in the Museum's collection. The digital data was then used to produce a full-scale replica of the sculpture using pulverised limestone from quarries local to Elche. The tests, samples and documentation relating to the production of the replica will be included in the exhibition along with photographs, a film and 3D animations of the digital data, while copies of the digital data itself will be presented to the Museo MARQ and to the Museo Arqueológico Nacional as valuable digital archives to aid all future study of The Dama de Elche.

The adaptation of digital technology to document and replicate heritage raises unique challenges that require skills and knowledge from a wide range of industrial fabrication techniques, software writers and conservation skills. This is a new and highly specialised field of work. Factum Arte is a company at the fore-front of the use of digital technology in this way. Factum Arte has already successfully completed a digital replica of a section of the burial chamber of the tomb of Seti I which was exhibited at the Museo Arqueológico Nacional, Madrid. This digital replica was produced using a specially designed laser scanning system, the Seti Scanner, industrial routing techniques and a system of 3D digital pigment printing designed by Factum Arte. The impressive realism of the replica was achieved by scanning the surface of the tomb at a resolution of a tenth of a millimetre – a resolution that had never before been achieved in practice. All of the production processes

were rigorously adapted and controlled to ensure that none of the data was lost or compromised so that the replica would be as accurate and objective as possible. This constant attention to detail resulted in a replica that is close to the original in both look and feel.

### WHY USE DIGITAL TECHNOLOGY?

A traditional technique would be to make a mould from the object and cast a replica in plaster. This can produce a very realistic effect but requires full physical contact with the original which can result in damage to the surface. An alternative method would be to copy the object by hand in similar materials. Again, the results can be very realistic but, crucially, making a copy by hand is a subjective process dependent on the skill of the artist. The experience of seeing a hand-made copy can be quite different from the experience of seeing the original. The digital techniques used by Factum Arte are not only objective, but are also highly accurate. They are a fast and efficient way to record an object without requiring any physical contact, and because the data is of a very high resolution when it is used to fabricate a replica the resulting object looks physically identical to the original.

Now that it has been demonstrated that it is possible to produce an accurate replica of such high resolution there is the opportunity to redefine the many uses of such replicas for the documentation, study and preservation of cultural heritage. The popularity of the Seti show at the Museo Arqueológico Nacional challenges the view that replicas are in some way inferior and suggests that they can become a valuable addition to museum displays without the audience feeling 'duped'. The technique of digital documentation also has a significant part to play in the study and conservation of heritage, such as the monitoring of deteriorating surfaces and close-range analysis. As this project shows, this modern technology has a valuable role to play in our museums and can be used to help protect and present our oldest heritage. As our heritage is continually under threat it is clear that there is ample scope for the application of this technology not only at the museums and monuments of Spain, but at historic sites around the world.

## THE USE OF REPLICAS IN HERITAGE

Copies have been known throughout the history of art, from Roman copies of Greek statues, to 18th century imitations of the Roman copies, as a way for famous works to reach a wider audience. Within the Islamic tradition of miniature painting copying is an accepted way to deepen understanding and appreciation of an established canon of great works. The process of copying is still used in art academies as a valuable tool for learning about art. Today there are many ways in which copies and reproductions can be used to contribute directly to the protection of art and artifacts and also to aid in education and study.

Historic sites and buildings are often decorated with carvings, frescoes or mosaics which, if exposed to the elements, are in danger of severe deterioration or even destruction. However, these art-works can be saved by well researched preservation policies and limiting visitor numbers. In some cases, like the Romanesque frescoes from the church of San Clement in Taulí, they have been removed to the protected environment of the Museum of Catalan Art in Barcelona. If they were replaced with an exact replica the visual integrity of the original site would be maintained. Conversely, replicas of isolated and inaccessible monuments can be made for display in museums so that they can be seen in the context of other museum displays and by an audience that would otherwise never have the opportunity to see them. On a grander scale, entire sites can be replicated, such as the Altamira caves. These caves and their neolithic paintings were under threat from the environmental hazards posed by heavy visitor numbers. The construction of a full-scale replica, housed in a purpose-built museum at Altamira, has made the caves accessible while protecting the originals, with the added advantage of all the facilities that a museum can offer. Another advantage is that the revenue generated by the Altamira museum can be used to fund the conservation and preservation of the caves.

Reconstructions can be used in museums to create educational displays, but they are also used experimentally by archeologists and historians to help answer questions about ancient civilisations and how they lived. The use of replicas in research and study, rather than original objects, helps to conserve the originals by protecting them from potential damage from handling.

This is particularly important for objects with vulnerable surfaces such as loose or flaking pigment, paper and even metals, which can be corroded by the substances in human sweat. Replicas can also be used in museums as objects designated for handling by visitors. This allows people to learn by touching and feeling, but is also a powerful resource for blind and partially sighted visitors.

### INITIAL RESEARCH

Before work began Factum Arte carried out some initial research to gather together all relevant information on The Dama De Elche. Publications, records and insights from historians and specialists were all useful because every aspect of the sculpture's history has had an affect on its surface. In order to establish the best working method it was important to find out how it was made, the materials and working methods, its burial and about the sculpture's subsequent journey since being discovered.

## THE DAMA DE ELCHE

The Dama de Elche is the most well known example of Iberian Art. It is famous not only for its beauty and the skill of its intricate carving but also for its excellent state of preservation. The serene and enigmatic expression on the sculpture's face has provoked many unanswerable questions about who she may be and why the sculpture was made, and the dress, ornamentation and jewellery give a tantalising insight into the sophistication of a lost, ancient culture of which precious little remains.

### A BRIEF HISTORY

The sculpture was discovered by chance on the 4th August 1897 by Manuel Campello Esclapez, a young worker employed by Dr. Manuel Campello y Anton, on part of Dr. Campello's land at La Alcudia, the site of the ancient city of Illici. Remarkably, the sculpture was intact – it was within a mysterious stone structure which had succeeded in protecting it from being destroyed over the centuries. When it was found it suffered only minor accidental damage from Manuel Campello's pickaxe. It was immediately recognised as an extraordinary find and displayed on a balcony in one of the main squares in Elche. Two weeks later Pierre Paris, a respected French archeologist, was visiting Elche to see the local mystery play held every August in the town. By the end of the month he had purchased it from Dr Campello for the Louvre in Paris. He paid 4000 French Francs and when the sculpture arrived in Paris it was exhibited as 'La Dama de Elche'.

In 1941 the sculpture was brought back by the Spanish government as part of an exchange of art-works with the French government. When The Dama de Elche was exhibited at the Prado in Madrid it was a great moment of national pride. Today, shown alongside other Iberian sculptures at the Museo Arqueológico Nacional in Madrid, it is clear that The Dama de Elche is the finest example of art from this remarkable period of Spanish history. Having been continuously

studied and written about, even making an appearance on Spanish bank notes, the sculpture is now established as a national symbol of Spanish culture and heritage.

The dating of The Dama de Elche is the subject of some controversy but it is generally believed that the sculpture dates back to the 4th century BC, based on related finds at La Alcudia and the history of the ancient site of Illici. The city of Illici was cited by both Strabo and Pliny as one of the most important cultural and commercial centres on the Iberian peninsula. It was founded in the 6th Century BC and was finally destroyed by the Carthaginian armies of Hamilcar in 228 BC. However, some scholars, intrigued by the style of the carving, particularly of the facial features, date the sculpture to the Hellenistic or Roman periods. Some art historians have also questioned the authenticity of the piece. There have been many suggestions about the identity of the lady and the purpose of the sculpture. The lavish jewellery and elaborate head-dress suggests that she may have been Iberian royalty or a priestess, and the delicate features of her face may have been carved as a portrait. There is also a recess carved into the back which suggests that the sculpture may have originally had a funerary or votive function.

## THE CONDITION OF THE SCULPTURE

The Dama de Elche is carved from a solid block of limestone which has been identified as a stone local to the area around Elche, but the site of the quarry which the stone came from has not been identified. Limestone of this kind is particularly common in the Levantine and Andalusian regions. It is coarse grained and very soft, particularly when freshly cut, making it very easy to carve. Prolonged exposure to the air causes the stone to dry out and harden. Most of the sculpture shows a high degree of finish, but around the base and rear there are a number of clearly visible chisel marks. Given the naturally soft texture of the stone it is even more extraordinary that the sculpture was recovered with very little damage. The most delicate detail of the of the headress remains visible and there are even traces of pigment suggesting that it was once brightly painted. Early, fanciful reproductions suggested that the drapery was once

blue, with red undergarments and headress, and golden ear pieces and jewellery. However there is no evidence of any gold on the sculpture, or of blue pigment. The only evidence of colour is some traces of red pigment on the lips, headress and neck.

It is reasonable to assume that The Dama de Elche has been cleaned since its discovery, certainly on excavation, and most likely several times over the years as it has gone between institutions in France and Spain. The surface of the sculpture is covered with fibres embedded into the superficial dirt. This could be the result of surface cleaning using the bundles of fibrous hemp readily available in local hardware shops, but the fibres could also come from fine roots that are found in the soil surrounding the area where the statue was discovered. The ear pieces show clear signs of having been cleaned and the encrusted dirt raked out of the indented surface with a sharp metal tool. However, deposits remain, particularly at the back of the head where there is evidence of iron oxide red pigment and a reticulated encrustation. This crusty surface could be the result of lime build-up on the surface during the time of burial, but it could also suggest that the surface originally had a gesso-like coating.



## GATHERING THE DIGITAL DATA

The 3D digital data was recorded using laser scanning technology. Both commercially available and specially designed systems were used. One of the most significant problems concerned the complicated three-dimensional form of the sculpture which had to be recorded without losing resolution or compromising the overall dimensions which are critical to make a copy that is meaningful for the conservators. It was particularly challenging to record areas which are deeply recessed because these areas are hard to access with the laser scanner. Another difficulty was the extremely fine detail of the surface. Not only is the carving highly intricate in places, but also the aging of the stone has resulted in a finely textured surface with tiny pits and abrasions. It was essential to record the character of these surfaces so that they could be accurately reproduced. Deposits and traces of pigment add to the complexity of the surface. The same attention to detail was applied to every stage of the process from data gathering to production and finishing because the accuracy and resolution of the data should not be compromised by subsequent processes.

Three different laser scanning systems were used to scan The Dama de Elche: two to capture the overall shape and surface of the sculpture and one to capture the surface detail. The data sets from the three scanning systems could then be directly compared for accuracy and resolution. This is the first time a comparative study between systems has been carried out on a major sculpture. The Dama de Elche was also conventionally and digitally photographed. Every precaution was taken to ensure that the sculpture was not at risk from any kind of damage. The sculpture was removed to a private room in the Museo Arqueológico Nacional where the data gathering was carried out under the supervision of the museum's conservation staff. All handling of the sculpture was carried out by SIT Transportes Internacionales. Its condition was checked prior to its removal from the vitrine and on its return after the scanning. All stages of the work were documented with photographs.

## LASER SCANNING

Digital 3D laser scanning technology was developed for use in manufacturing industry to assist product design and prototyping, but has since also found applications in entertainment and gaming industries. There are many different systems available but most operate using the principle of triangulation: the scanner emits laser light which is aimed at the object being scanned. Sensors in the scanner detect the position of the projected laser light and its location is calculated using special computer software. By moving the light across the object the entire surface can be mapped. One of the great advantages of this technique is that only the laser light makes contact with the surface allowing even very vulnerable surfaces to be scanned without risk. There is no need to apply markers or measuring devices to the surface or even to touch it at all. The lasers used in laser scanning are the same type of low-power red light laser used in barcode readers and CD players and are not capable of generating enough light emission to cause damage. Factum Arte has rejected the use of point lasers and works with strip lasers that spread the light intensity over a strip that varies in size depending on the scanning system. The strip of red light is continually in motion as it scans the surface. It is not directed at any one spot for more than a fraction of a second. Scanning is carried out with low ambient light levels so that very low powered lasers can be used.

For the production of the replica it was essential that the data should be in a form that could be used to produce a high-resolution three-dimensional object. Today, most scanning systems can provide data that is adequate for screen-based applications such as virtual reality. The production of physical facsimiles requires significantly higher resolution data which is then difficult to handle during the processing that is required for 3D fabrication. This usually results in an averaging of the data (or in the worst case, data loss or distortion) with the knock-on effect that the 3D model is not crisp enough and lacks the necessary detail to convince the eye. It was therefore essential to scan to the highest possible resolution and to minimise post-processing at all times.

## SCANNING THE OVERALL SHAPE

The two systems used for the overall scanning of the sculpture were the Minolta Vivid 910 and 3D Scanners' ModelMaker W.

### MINOLTA VIVID 910

All work with the Minolta Vivid 910 was carried out by Subipro, a company based in Bilbao which specialises in laser scanning and rapid prototyping. Additional technical support was provided by Minolta through their agent in Valencia, Aquateknica. The Minolta scanner was selected for this work as it had been successfully used on the Michelangelo Project, a scanning project to record Michelangelo's David carried out by Stanford University. The Vivid 910 scans the object with three rapid passes of the laser strip and the data is averaged from these three passes. In addition, a colour image can also be captured and viewed on screen. The sculpture was placed on a Minolta turntable linked to the scanner so that their relative positions remained constant allowing true points in three dimensional space to be recorded. The turntable was gradually rotated in movements of 15 degrees and the scanner repositioned until every facet of the piece had been recorded and there were no holes in the data. All of this was done at the highest workable resolution of the Minolta scanner, between 150 and 200 microns along the scanning strip and between 200 and 600 microns between the scanning lines. The sculpture was also placed on its back so that the base could be scanned. The scanning using the Vivid 910 was carried out over four days. A total of 961 different views were recorded producing 1.2 gigabytes of data. Once the scanning was completed all of the different scans were then merged together to form one complete unit. This was done in Italy by ISTI CNR who took four weeks to assemble the data.

### MODELMAKER W

The ModelMaker W is made by 3D Scanners UK. Factum Arte's previous collaboration with 3D Scanners was to carry out laser scanning in the tomb of Seti I in the Valley of the Kings, Egypt, which included testing the ModelMaker system in the tomb. The

ModelMaker has also been used in other heritage projects to record sculptures and low relief carving for documentation and virtual reality purposes. The ModelMaker system consists of a scanning head mounted onto a Faro arm attached to a tripod. The scanning head is designed to be held in the hand so that the path of the laser strip is controlled manually. The Faro arm is articulated with seven degrees of movement so the operator has ample freedom to manoeuvre the scanning head. There is a measuring error inherent in each joint of the Faro arm producing a cumulative error of about 100 microns. In this way the ModelMaker can scan undercuts and around corners without the need for constant repositioning of the tripod. This also means that during the scanning the sculpture need not be moved. This is one of the major differences between the Minolta and ModelMaker systems. The scanning of The Dama de Elche was carried out over three days. The data has a constant resolution of 100 microns along the scanning line and between 250 and 500 microns between the lines. The data were merged and meshed, using a 300 micron mesh, by 3D Scanners using Raindrop Geomagic software. All post processing was carried out without optimising or data reduction. It was completed in three days and the files were then thoroughly checked and analysed.

#### COMPARING THE DATA

After the completion of the scanning and post-processing both data sets were sent to 4D Concepts in Germany and fabricated using a Z Corp 3D printer. This is the first time a direct comparison has been carried out using scanning systems with similar technical specifications and working with technicians from the companies that sell the product. The data from the Minolta was significantly inferior to the ModelMaker and as a result was discarded. Due to the poor quality of some of the files and the errors in scanning there was significant distortion in the overall form in all axes causing a warping effect. There was clear evidence of data reduction during the processing but, in addition, analysis of the data files and the 3D print suggest that design faults in the turntable resulted in a spiralling distortion of about 2cm. The Minolta model also contained errors in overall size and absolute positioning of points in 3D space rendering

post processing very difficult and the data meaningless for serious conservation and academic study. In contrast the ModelMaker has recorded an accurate copy with crisp surface detail that required significantly less post processing time than the Minolta data. The 3D print from the ModelMaker data was used for the basis of the facsimile and the Seti Scanner data was incorporated into this model.

#### SCANNING THE SURFACE DETAILS

##### SETI SCANNER

The Seti Scanner is a system designed by Factum Arte. This system was designed for the specific purpose of scanning the low relief surfaces in the tomb of Seti I. It cannot record areas which are inaccessible to the laser strip, such as undercuts, because it only operates on three axes, and it also cannot accurately record relief beyond its depth of field. This means that the Seti Scanner was not able to scan the entire Dama de Elche without further modifications, however, it was decided to use the Seti Scanner to scan areas where the surface detail is of critical importance because this scanning system is able to capture data at a higher resolution than the other two systems that were used. Areas scanned using the Seti Scanner included the face, the ridged lattice patterning on the outside of each of the ear pieces and a part of the back with characteristic encrustations on the surface.

The Seti Scanner is a 3D laser scanning system that consists of a high resolution Reversa 25 scanning head, made by 3D Scanners UK, mounted onto specially constructed, servo driven xyz linear guides, controlled by a CNC. It has a maximum working resolution of 100 microns and a depth of field of 25mm. Once the scanner has been set up it scans in a series of horizontal passes. The scanning head emits a single strip of laser light which passes across the surface of the object as the scanning head travels along the linear guide. The position and movement of the scanning head is fully mechanised and controlled by computer. After each horizontal pass the head is automatically re-positioned to record another pass. It took about four and a half hours to record the complete face of the sculpture.



The Seti Scanner uses Riscan software to capture and display the data but additional software was written by Factum Arte to remove scanner artifacts, reposition the scanning head and merge the data from each pass. The Riscan software has a number of specialist features including a colour-coded display to indicate relief, merging features, gap filling and data cleaning. The Seti Scanner was designed to gather optimum data sets with maximum surface detail for the specific purpose of the production of high resolution replicas. It is particularly important to record the superficial detail to a high resolution so that complex surfaces can be faithfully reproduced. Another significant aspect of the data is that it can be prepared for fabrication by industrial routing without meshing as it is cut directly from the point cloud. The scanned data requires only a minimum of cleaning. This not only reduces the amount of work, time and expense but also ensures that the integrity of the data is maintained.

## DOCUMENTATION

In addition to the laser scanning, photographs were taken of the scanning process and of the sculpture's surface. These were used, alongside other notes and observations, to record the work carried out and to record the sculpture itself.

This was a unique opportunity to carry out documentation of The Dama de Elche which has never been studied in such detail before. Copies of this archive will be deposited with the Museum MARQ and with the Museo Arqueológico Nacional. All aspects of the project were also recorded on video with interviews, 3D animations and explanations of the complex procedures used in the production of the replica.

## PRODUCTION

After extensive tests it was found that a combination of techniques would be needed to produce the replica. There are a number of different processes used in industry to produce three dimensional prototypes from digital data. These processes are referred to as rapid prototyping. A model can either be built up in layers using stereolithography, lasersintering and 3D printing or it can be cut from a solid block using industrial milling machines, a process referred to as milling, engraving tooling or routing. Tests showed that routing was the best approach for reproducing the fine detail that was essential when trying to capture the character of the surface. However, routing is less suited to producing a model in the round, a task suited to the Z Corp 3D printer.

It was decided to produce two versions of the replica using two different approaches to the production of the desired surface. One approach involved covering a model, produced by the Z Corp 3D printer, in a fine paste of pulverised stone, the other approach involved constructing a model out of sections of Z Corp and routed data, creating a mould of this model and then casting the entire replica from this mould in a mixture of pulverised stone and resin medium. These two approaches differ fundamentally in the way they recreate the surface. For the first version the surface is built up using a variety of techniques, while the second version relies on the high-resolution information in the mould and the natural textures of the materials to create a realistic surface.

## SOURCING AND TESTING OF MATERIALS

The block of limestone from which The Dama de Elche is carved has been identified as being local to the area around the town of Elche so samples of materials were gathered from this area. The use of natural materials significantly adds to the realism of the finished replica and by using stone that is as close as possible to the original the replica is faithful not only in general appearance, but also in physical

substance and weight. This also means that the replica will probably age in a similar way. After extensive searching some limestone fragments were collected from a disused quarry about 10 kilometers north of Elche near the road to Madrid. These fragments were selected for the specific weathering and surface colouring that resembled the surface of the sculpture.

Back at the studio the fragments were pulverised and sieved. Tests were carried out, using small quantities of resin and conservation mortar as a binder, to find the best grain size to reproduce the look and feel of the original surface. Different earth pigments were also tried both as part of the recipe and as surface treatments. It took over 100 tests to find the best combination of materials. Further tests were needed to try and devise the best way to reproduce the effect of the burial and aging. These tests used samples of soil that were collected near to La Alcudia, the site where the statue was unearthed, and soils from around Elche. When trying to reproduce the colours and textures it was necessary to constantly refer to the original sculpture. Detailed notes and photographs taken at the time of the scanning provided essential information, but a direct comparison was the most reliable way to assess how well the replica resembled the original.

### 3D PRINTING

The rapid prototyping was carried out by 4D Concepts at their workshops in Gross-Gerau, near Frankfurt, using the data gathered by the Minolta and ModelMaker scanners, although the model fabricated from the Minolta data was subsequently rejected. Tests were also carried out using stereolithography but the horizontal banding is too visible in the commercially available machines so this approach was rejected until more software and mechanical modifications can be made.

The models were made using a Z810 3D Printer (made by Z Corporation, Boston, USA). The Z Corp 3D printer uses a finely grained plaster-like material. A thin layer of the dry material is spread onto the build area and then water, which acts as a binder, is printed onto the area to be bonded. As soon as this has cured a new

layer of power is spread on top. As the process continues the model builds up layer by layer. When the printing process is finished the build platform is removed and the loose powder cleaned away to reveal the 3D print. The model is then infiltrated with epoxy resin to make it durable. The 3D printer is capable of building prototypes with a maximum volume of 600 x 500 x 400 mm.

For The Dama de Elche project each layer was 100 microns thick. This is the maximum resolution of the 3D printer and working at this resolution significantly increases the printing time. After preparing the data for printing the first test took 28 hours to materialise. It was printed at an angle of 30 degrees to minimise the visible signs of the layering used to build the 3D form. The eye is much more sensitive to regular horizontal or vertical artifacts and this was the optimum solution to minimise the problem. The main requirement was that the model must be robust enough to withstand the casting process and that the surface could be hand finished. From data to model it took three days to create each of the Z Corp 3D prints. Two models were made from the ModelMaker data, one for each version of the replica.

### ROUTED SECTIONS

The routed sections were cut using the data from the Seti Scanner. This work was carried out by Delcam UK at their tooling workshop in Birmingham, using a three-axis router. The data from the Seti Scanner does not need processing or meshing before it is prepared for routing, thus reducing the time spent on data manipulation, but, more significantly, this means that the routed sections are made from true data that has not been compromised in any way. Delcam used a complex cutting strategy that involved cutting four times with progressively finer cutting heads on carefully selected areas. Some of the cutting heads are ball nosed with straight sides, others are conical with 5 degree angled sides. The tip of the cutting head used to do the final cut had a radius of only 0.1mm and the face alone took over 60 hours to cut. The material used was a dense polyurethane board – a standard top quality material for industrial routing. The choice of routing material is critical because it must be

dense enough to retain detail and very stable so that there is no risk of distortion through expansion and contraction. A total of four sections were cut in this way. Some initial tests were done to cut directly into limestone, with very promising results. However, it was considered too impractical to produce the entire sculpture this way within the time-frame.

### FACSIMILE VERSION ONE

For the first replica a whole range of techniques were used to recreate the appearance of weathered stone on the surface of the Z Corp 3D print. All the production work of the finished facsimiles was carried out in Factum Arte's workshops in Madrid.

#### COVERING THE SURFACE OF A 3D PRINT

The model was first coated with a thin mixture of restoration mortar and pulverised limestone, with pigment added to match the internal colour of the original limestone sculpture. A second coating of pulverised limestone mixed with water was added selectively using stencils in order to mask off small areas, particularly on the face. A top coat of slightly more yellow pulverised limestone mixed with liquid glass (potassium silicate), a mineral binder that produces a brittle coating, was then applied over the entire surface. When this surface is subjected to heat it cracks and areas which had been coated with the limestone and water mix could then be brushed off. This results in areas of minute relief and crackling which mimics the abraded surface of the stone. Once this surface has been achieved the pigment residues are applied locally by hand, using iron oxide pigments. The entire sculpture is then coated with a mixture of mud from Elche and water. This mud has a strong red colour and when cleaned away using wood and metal tools, gives the surface the correct colour and character. The finishing touches are added by brushing with a brass brush, dusting with a tinted mixture of calcium carbonate and talc, and rubbing with fingers.

The overall effect of these techniques is the creation of a realistic imitation of the surface of The Dama de Elche created by using

materials which are very similar to the originals. The textures achieved have the same qualities as the original and, to a certain extent, the position and shape of the cracks and reticulations are dictated by the surface of the 3D print. However, each minute detail does not match the original exactly.

### FACSIMILE VERSION TWO

The second 3D print was used to make a cast replica which incorporated sections of routed data from the Seti Scanner. The two different approaches were tested in order to understand the complex relationship that exists between true surface detail and surface complexity. In version one of the facsimile the surface is not identical to that of the original but it has a similar surface characteristic that mimics the qualities of the original. In Version two the surface detail is more accurate and the manual interventions kept to a minimum.

#### ASSEMBLING AND CASTING THE MODEL

Moulds were made of the 3D print and all of the routed sections. These pieces were then all cast in plaster and the plaster pieces assembled into a complete model. Plaster was chosen because it is easily worked and hand finished, but using moulds also meant that the 3D print and the routed sections could be kept as master copies. A final mould was made from the plaster model and the replica cast from this mould. All of the moulding, casting and finishing stages of the production were carried out at Factum Arte's workshops in Madrid. Making a silicon mould of the 3D print was a task requiring careful planning and great manual skill because the complicated form of the sculpture demanded a mould of over a dozen individual pieces. Each piece of the mould had to fit to its neighbours perfectly and the mould had to be designed so as to be readily dismantled and reassembled. This stage alone took 10 days. When all of the pieces had been cast in plaster the casts of the routed sections were carefully incorporated by hand into the plaster cast of the 3D print. This was achieved by carefully measuring and marking up the cast of the 3D print before cutting out the unwanted areas. Each piece of cast routing was then trimmed to fit. The joins were finished by hand

to produce a seamless whole. Again, this operation required meticulous planning and skill, although another advantage of using plaster casts was that fresh sections could easily be cast from the moulds, if needed. The moulding process was then repeated with the assembled plaster model.

The replica was cast in a specially developed recipe of limestone and resin, pigmented to resemble the internal colour of the original sculpture. Hand-finishing was then used to colour the surface. The techniques used were similar to those used on the Z Corp 3D printed replica, although interventions were kept to a minimum so as not to interfere with the objectivity of the digital data.

## CONCLUSION

The project to replicate The Dama de Elche has been an unprecedented opportunity to document and study this remarkable sculpture. The scanning has also enabled, for the first time, a close comparison of three different scanning systems. Each system has its own specifications and limitations which resulted in data sets of differing resolution and quality. There is clearly a need for such objective comparisons so as to verify the capabilities of each system. The work has necessitated a close examination of the surface, and the tests to try to reproduce the surface effects have given an insight into the processes that resulted in the complex textures and colours. Such research is a valuable addition to future studies of the sculpture. The production of two replicas using two different approaches to the reproduction of the weathered stone surface has enabled a direct comparison between hand-rendered and machine-rendered surfaces. Both replicas are the most accurate copies of a sculpture ever made.

The techniques used in this project have much to offer. Replicas have a place, not only in museums, but also as part of a broader management strategy for the future protection and preservation of heritage. The data gathering has resulted in an accurate, high-resolution digital record which will be a vital archive for the monitoring of the sculptures condition. It will also be an invaluable additional resource for research in the future. The true value of this archive will become apparent as it is used for academic and historic research to learn more about The Dama de Elche and its place in the history of Spanish culture.

## APPENDIX



## FACTUM ARTE

Factum Arte is a company which specialises in projects for artists and institutions that involve digital mediation and fabrication. These projects often present a range of technical challenges which Factum Arte tackles with a combination of the development and application of new technologies and the use of more traditional manual skills. The production of high-resolution replicas for the heritage sector is one of Factum Arte's key areas. In the two years since Factum Arte was established it has developed a unique working method, analysing the specific needs of each project and developing the hardware and software that is required whenever these are not commercially available. Recent developments include the production of a purpose built 3D scanner for use on polychrome low relief surfaces in Egypt, the writing of specialist software to remove scanner artifacts and a software package for 3D retouching, the development of a dimensionally accurate flatbed pigment printer for printing low relief surfaces, and various innovations relating to the use of different methods and materials. Factum Arte has established a network of contacts with universities and research centres in Europe and has close links with companies developing and applying new technologies in Japan, America, Italy, Germany, Spain and the UK.

Other projects include the production of large-scale sculptures and limited-edition multiples for artists and architectural installations. Factum Arte also produces publications and documentary videos.



## TECHNICAL DETAILS

### SCANNING USING FACTUM ARTE'S SETI SCANNER

The Seti Scanner is a 3D laser scanning system designed by Factum Arte and built by Rapier Engineering, Corby, UK. It incorporates a Reversa 25H scanning head built by 3D Scanners (UK). The scanner was operated by Pedro Miro under the direction of Manuel Franquelo.

### SPECIFICATIONS FOR THE SETI SCANNER

**Reversa scanning head:** 3D data capture using two CCDs (640x480 pixels) at 45° angle to the laser strip controlled by a Surfa card (Image processing board). The Surfa board uses DSP processing of video data to capture surface shape in real time at over 14,000 points per second.

**Laser:** Class 3A

**Laser strip dimensions:** 60 microns wide at 95% focus, 25mm long

**Measuring range:** 25mm

**Resolution:** At a distance of between 8 and 10 cms from the surface the Seti Scanner captures point cloud data at a resolution of 60 microns.

**Z resolution:** 10 microns

**Z Accuracy:** 20 microns

**2 scanning modes:** Linear and fast linear, cylindrical and fast cylindrical

**Scanning speed:** 1000 points per second

**Data Formats:** U16, F32, IBL, IGS, VDA, and ASCII

**Operating software:** Windows NT compatible software will output data in a variety of formats to CAD/CAM or other surfacing or inspection software. Factum works with Ris over Windows NT in conjunction with other tools developed by Factum Arte.

## SCANNING USING THE MINOLTA LASER SCANNER

The laser scanning using the Minolta Vivid 910 was carried out by Subipro under the direction of Pedro Ignacio Fernandez de Retana. Subipro is a design and prototyping company, based in Bilbao, specialising in laser scanning and rapid prototyping. The scanning work was carried out by Miguel Boix from Aquateknica, Valencia.

### SPECIFICATIONS FOR THE MINOLTA VIVID 910

Product Name:	Non-contact 3-D LASER digitiser VIVID 910
Laser:	Class 2 (IEC 60825-1), "Eye safe" Class 1 (FDA). Controlled by galvanometer-driven rotating mirror
Exchangeable Lenses:	The Vivid 910 comes with three lenses (TELE: f=25mm, MIDDLE f=14mm, WIDE f=8). All of the lenses were used to record The Dama De Elche. Most of the work was done using the TELE: F 25mm.
Scanning Modes:	FAST mode : 0.3 sec. FINE mode : 2.5 sec.
Measuring Method:	Triangulation light block method
Precision:	Over 300,000 points with range resolution to 0.0016" (Fine Mode, Minolta's standard) Precision on Z axis: $\pm 0.008\text{mm}$
Accuracy:	$\pm 0.008\text{mm}$ (Condition: FINE mode)
Optimal Range:	0.6 to 1.2m

The post processing of the Minolta data was carried out in Pisa, Italy by ISTI CNR. Factum Arte analysed the data in Madrid using Rapid Form software. Rapid Form is an Advanced Polygon Editing Software. It is designed for automatic data registration, processing of captured data and conversion to various CG formats.

## SCANNING USING 3D SCANNERS' MODELMAKER W

3D Scanners (UK) is a UK-based consultancy and solutions provider of non-contact optical measurement systems, with clients in the

automotive, aerospace, manufacturing, and product design and heritage sectors. The company offers a wide variety of software solutions for non-contact and contact scanning, surface creation, solid modelling and inspection to provide the speed and accuracy demanded by its varied clients.

The ModelMaker scanning was carried out by Anthony Barker of 3D Scanners, over three days, using equipment sent from England. The files were then merged and meshed by Austin Fearnside at 3D Scanners in Coventry using Surfacer software.

### SPECIFICATIONS FOR THE MODELMAKER W35

Sensor head weight:	550g
Range, z axis:	50mm
Strip length, y:	20-35mm
point spacing, y:	0.1mm
Speed:	25 strips per second
Laser power:	up to 5mW, class 3A
Sensor functions:	standoff laser, stand off LED, stripe trimmer
Software functions:	Datum module, scan module, section module, mesh module

## Z CORF 3D PRINTING

The 3D printing was carried out using a ZTM810 3D printer by 4D Concepts, Gross-Gerau, Frankfurt under the direction of Peter Volz. 4D Concepts specialise in a variety of rapid prototyping solutions for shortening and optimizing product development processes. They offer complete solutions from CAD design through rapid prototyping and rapid tooling to production tooling. In building prototypes they work with rapid prototyping technologies such as stereolithography, lasersintering, 3D printing and others. Additional services include injection moulding tools, production mould tooling, five-axis milling, spark erosion and wire cutting. The Dama de Elche model was built on a ZTM810 3D Printer for large scale prototypes



with a build volume of 600 x 500 x 400 mm. The Dama de Elche 3D print used a plaster based powder with 100 micron layers. After receipt of data the printing of the model took 28 hours. After printing the model was infiltrated with epoxy resin to make it more durable and allow surface finish and duplication techniques. From data to model it took 3 days to create the model of The Dama de Elche.

## ROUTING

Delcam is one of the world's leading suppliers of advanced product development solutions for manufacturing industry. It has long been recognised as a specialist provider of design solutions for companies using complex aesthetic and ergonomic shapes, as well as being the world's leading supplier of CAD/CAM systems to the toolmaking industry and an innovative developer of advanced machining software. Delcam is the only international CAD/CAM company that operates an in-house Tooling Services Division. The data from Factum Arte's Seti scanner was prepared using Delcam's PowerMill NC software and was then cut on a three-axis Matsuura MC-800 VF Vertical Machining Centre using a spindle speed of 15,000rpm. The material used was Alchemie Modelling Board 959W, which has a density of 1.2g/cm<sup>3</sup>. The CAD data translation and preparation was carried out by Tony McKenzie and Dave Cooper, with NC programming and machining by Steve Taylor. Toolroom supervision was by Gary Mills and the job was managed by Brian Hawkshaw.

## THE CUTTING STRATEGY

The first rough cut was done using a 12mm solid carbide end mill with a 1mm tip radius machining to +1mm stock using a raster area clearance strategy. The second rough cut used a 6mm solid carbide ball nose machining to +0.3mm stock using a raster strategy. The finish cut used a 20deg inclusive angle solid carbide D cutter with a 0.1mm tip radius using a raster strategy and 0.03mm step-over per pass. A final finishing cut was used to pick out areas not accessible with the conical D cutter. This was done using a 1mm tip radius solid carbide straight-sided cutter. The strategy used was a combination of constant Z and 3D offset machining.

## DOCUMENTATION

All work was documented using conventional photography by Gonzalo de la Serna. Factum Arte also recorded all stages of the process using a digital camera and a large format camera.

## VIDEC

The Museum MARQ commissioned a 30 minute film to document all stages of the scanning, moulding, casting and finishing. This film was made by RC Madrid working in conjunction with Factum Arte.

RC Madrid: Gabriel Scarpa, Miguel Guillén, John MacGregor.

# PLATES



Plate 1 -  
*The Dama de Elche, limestone with traces of pigment,  
circa 4th Century BC, 56 x 52.5 x 34cm -  
Museo Arqueológico Nacional, Madrid.*



Plate 2  
*The Dama de Elche*

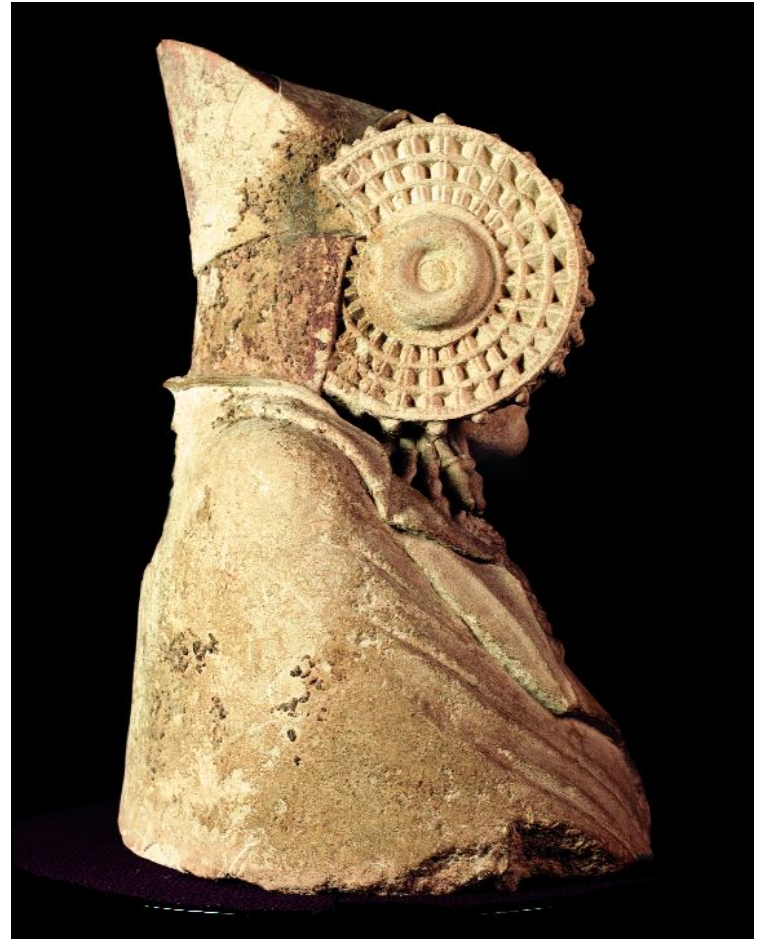


Plate 3  
*The Dama de Elche*



Plate 4  
*The Dama de Elche*



Plate 5

*The site of the discovery of The Dama de Elche at La Alcudia. The statue was found by accident buried in a small stone enclosure.*



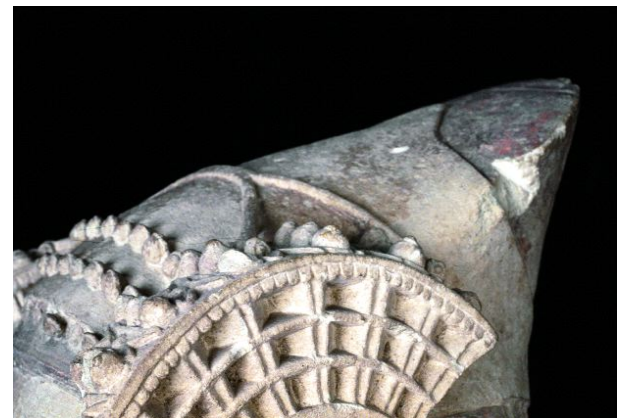


Plate 6 to 8

*A selection of details of the surface of The Dama De Elche.*

*A close analysis of the surface characteristics of the statue was critical to the realism of the copy.*



Plate 9 to 11

*A selection of details of the surface of The Dama De Elche*

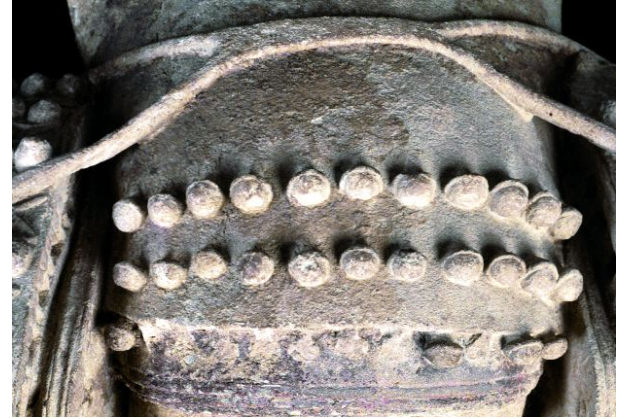




Plate 12

*The Dama de Cabezo de Lucero (after restoration by Vicente Bernabeu Plaza), limestone, circa 4th Century BC - MARC*

Plates 13 & 14

*The Damita N° 7.7007, limestone, circa 4th Century bc 20 x 7.5 x 5.5cm Museo Arqueológico Nacional, Madrid.*

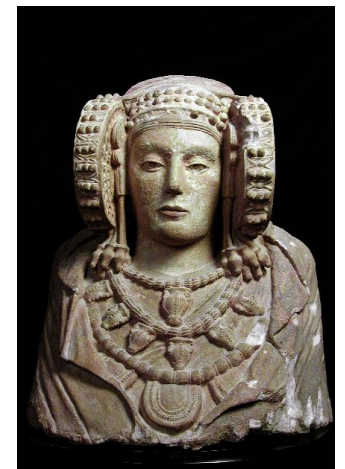
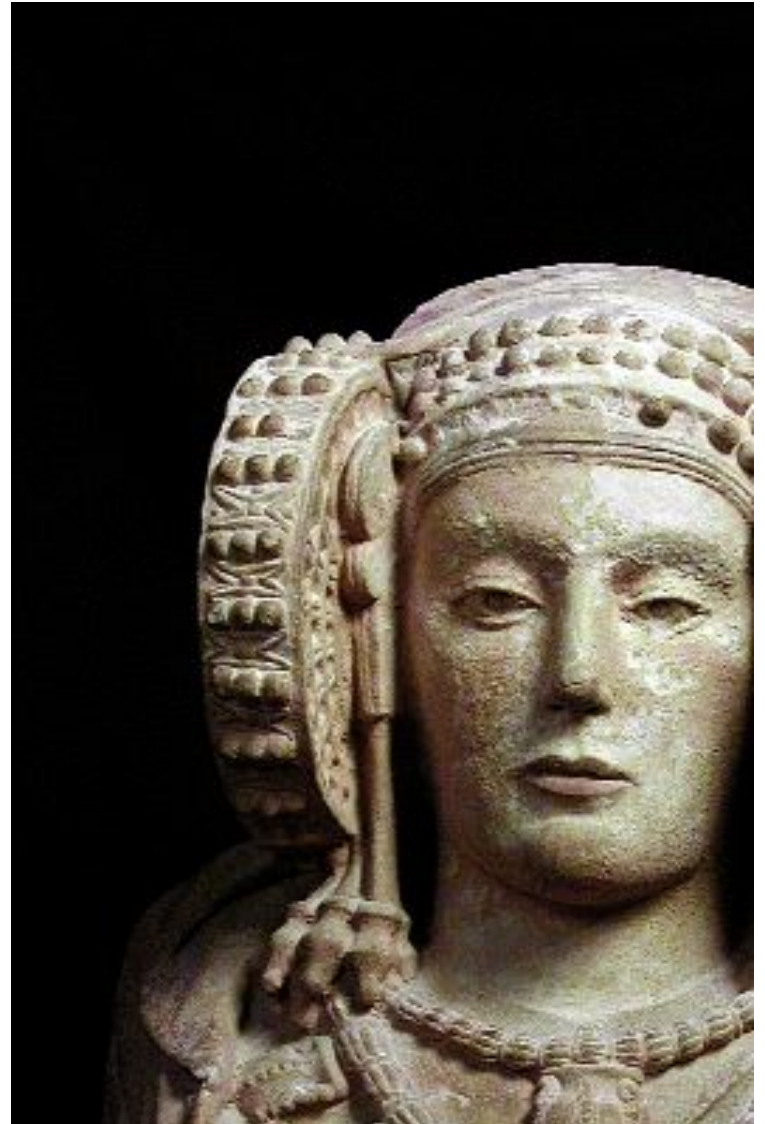


Plate 15

*The Dama de Baza, limestone with traces of paint, circa 4th century bc  
130cm high x 103cm wide - Museo Arqueológico Nacional, Madrid.*



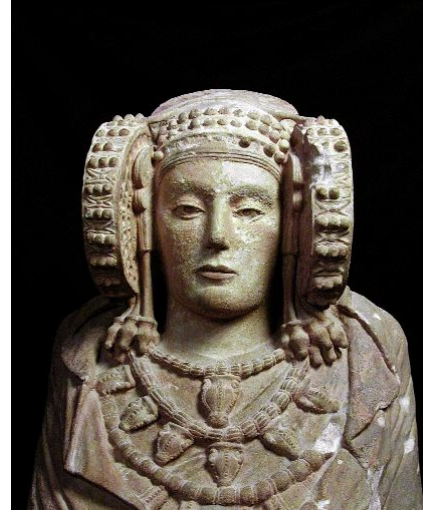


Plate 16  
*One Peseta Note*

Plate 17  
*Many early prints of the Dama de Elche suggest the statue was painted with red and blue pigment and covered with gold in places. However no traces of blue or gold remain.*







Plate 18  
*A selection of plaster and resin copies purchased at La Alcudia, Elche.  
Front view*



Plate 19  
*A selection of plaster and resin copies purchased at La Alcudia, Elche.  
Back view*

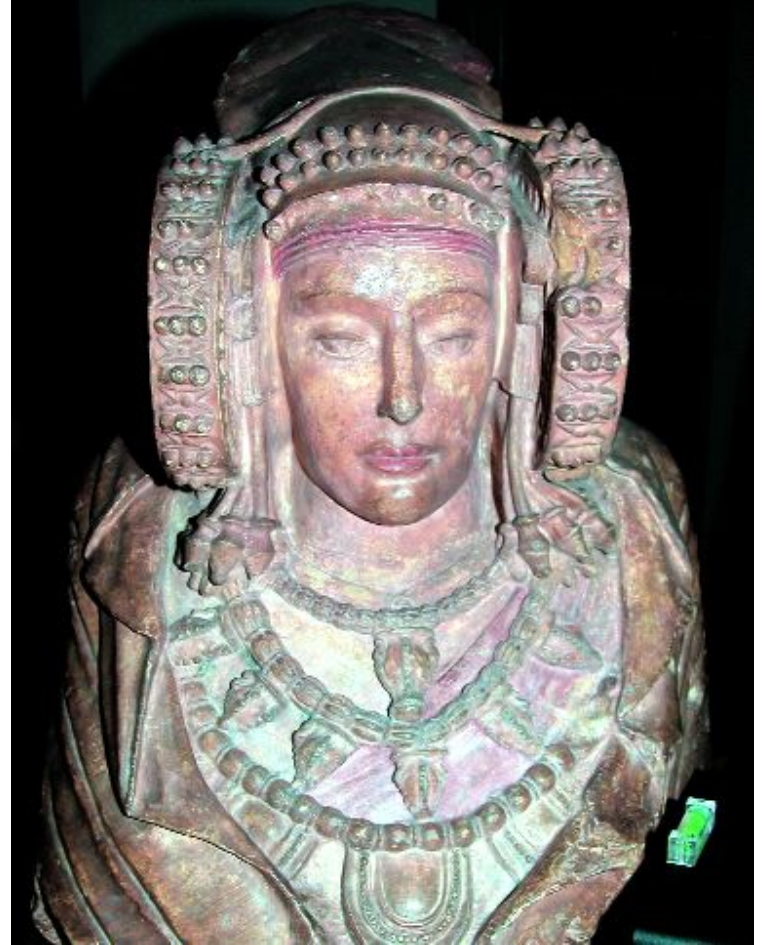


Plate 20

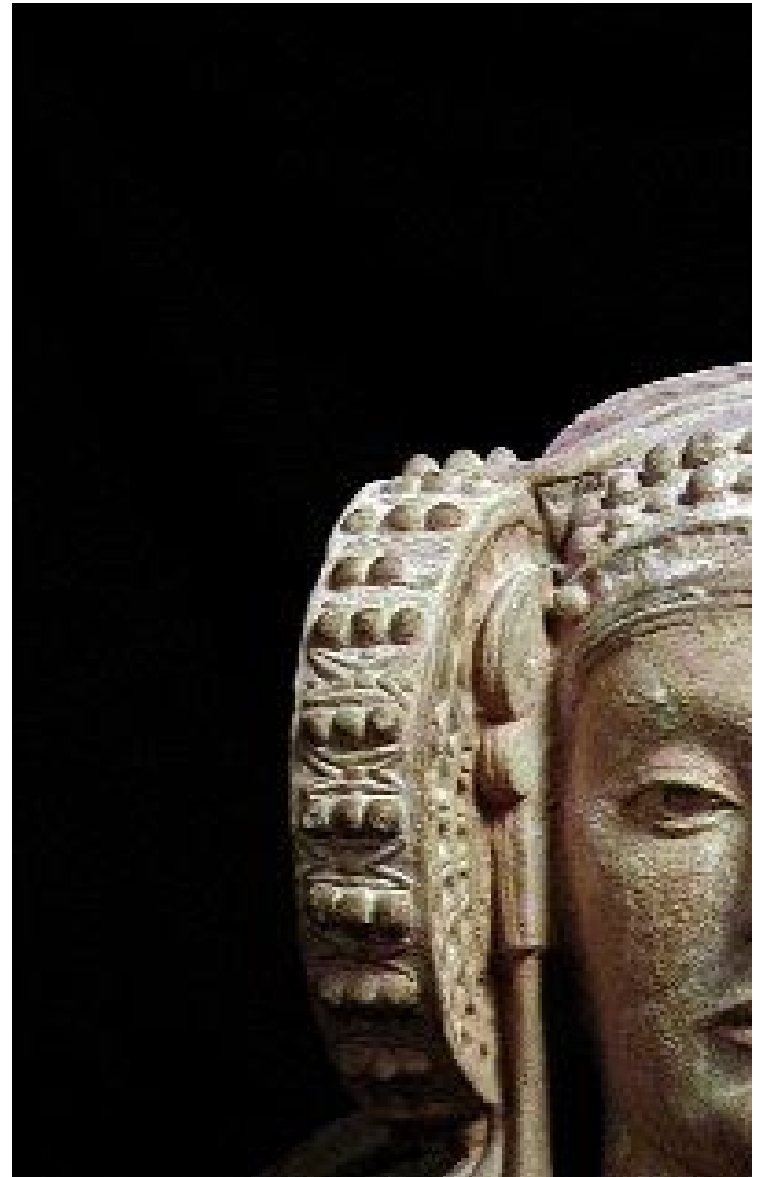
*Copy of The Dama De Elche by Ignacio Pinazo Martinez 1908, plaster and paint, 57 x 43 x 28cm.*

*Museo Arqueológico Nacional, Madrid.*

Plate 21

*Postcard of the sculptor Ignacio Pinazo Martínez working on his copy of  
The Dama De Elche in the Louvre, Paris, in March 1908.*

*Archivo Casa/Museo pinazo, Godella (Valencia)*





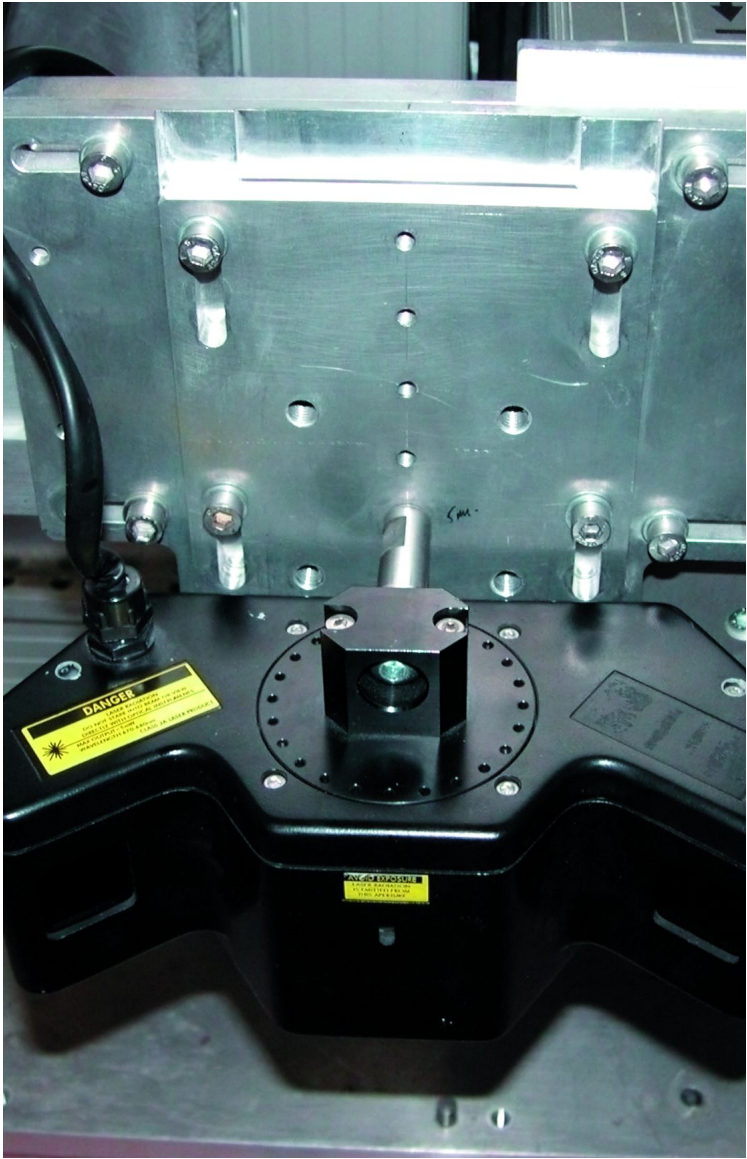


Plate 22  
*The The Reversa 25H mounted onto the Seti Scanner.*

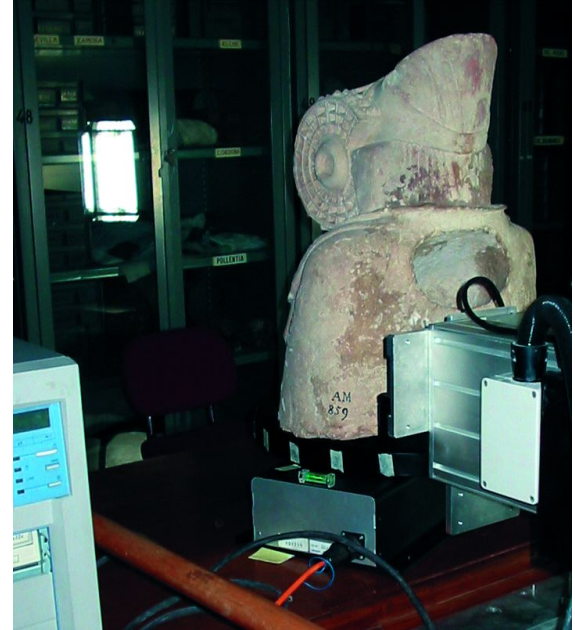


Plate 23  
*Seti Scanner working in low light levels in the Museo Arqueológico Nacional, Madrid*

Plate 24  
*The ModelMaker Scanner and the Faro Arm*

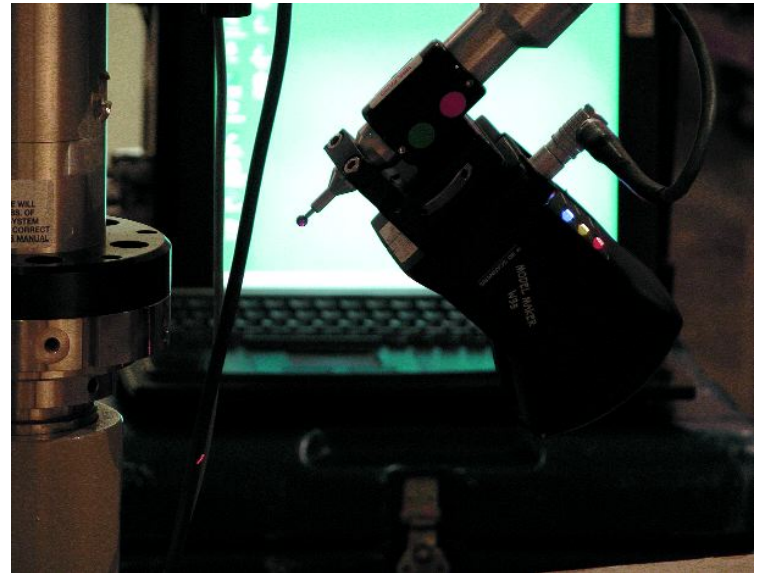




Plate 25

*The ModelMaker Scanner recording the surface of The Dama de Elche in the Museo Arqueológico Nacional, Madrid.*

Plate 26

*The Minolta scanner recording The Dama de Elche in the Museo Arqueológico Nacional, Madrid.*

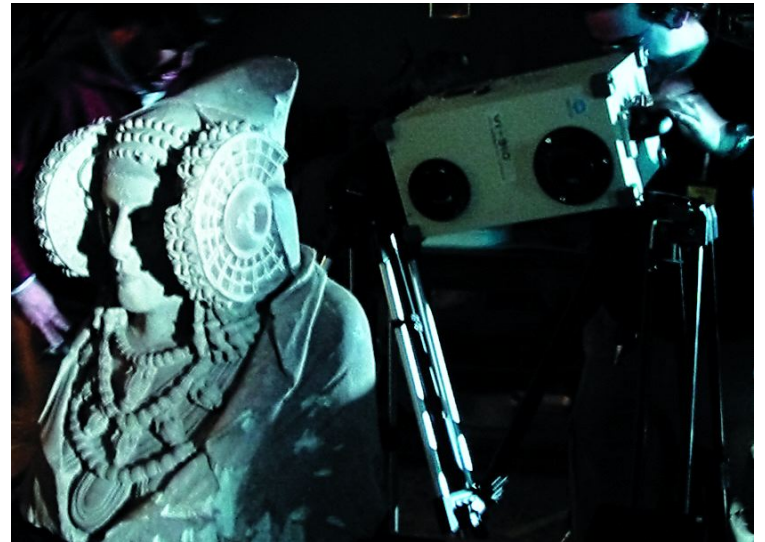




Plate 27

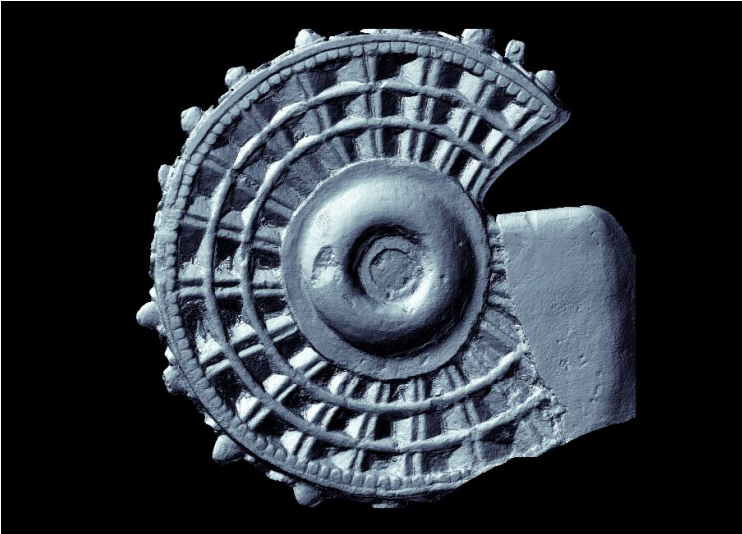
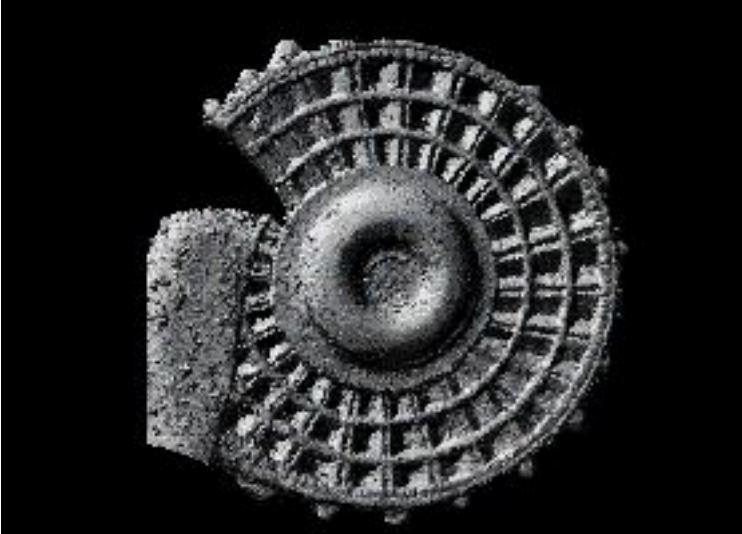
*The scanning strip from ModelMaker Scanner recording the surface of the sculpture. The V shaped line is a photographic artifact.*





Plates 28

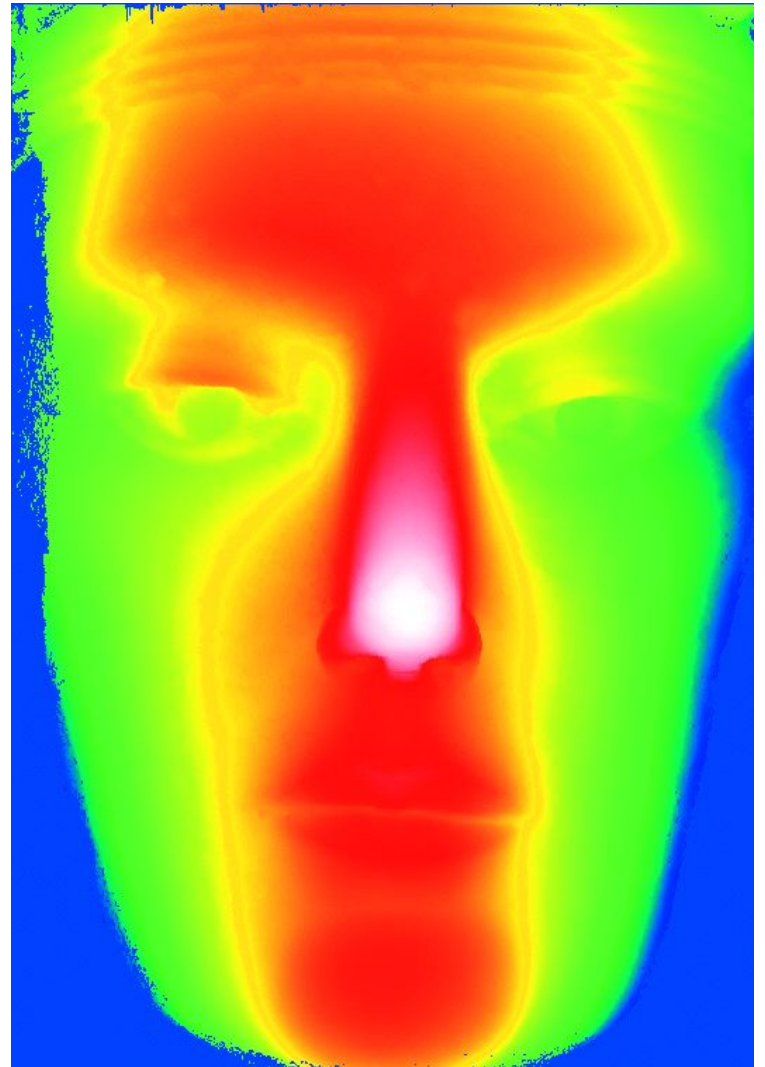
*Data from the Seti Scanner. This data is made up of points of 3D information positioned on a 100 micron grid and requires no meshing or post processing.*



Plates 29 & 30  
*Data from the Seti Scanner*

Plate 31

*Colour coded data from the Seti Scanner indicating the relief surface. The many different renderings of the 3D data can provide new source material for academics and conservators.*





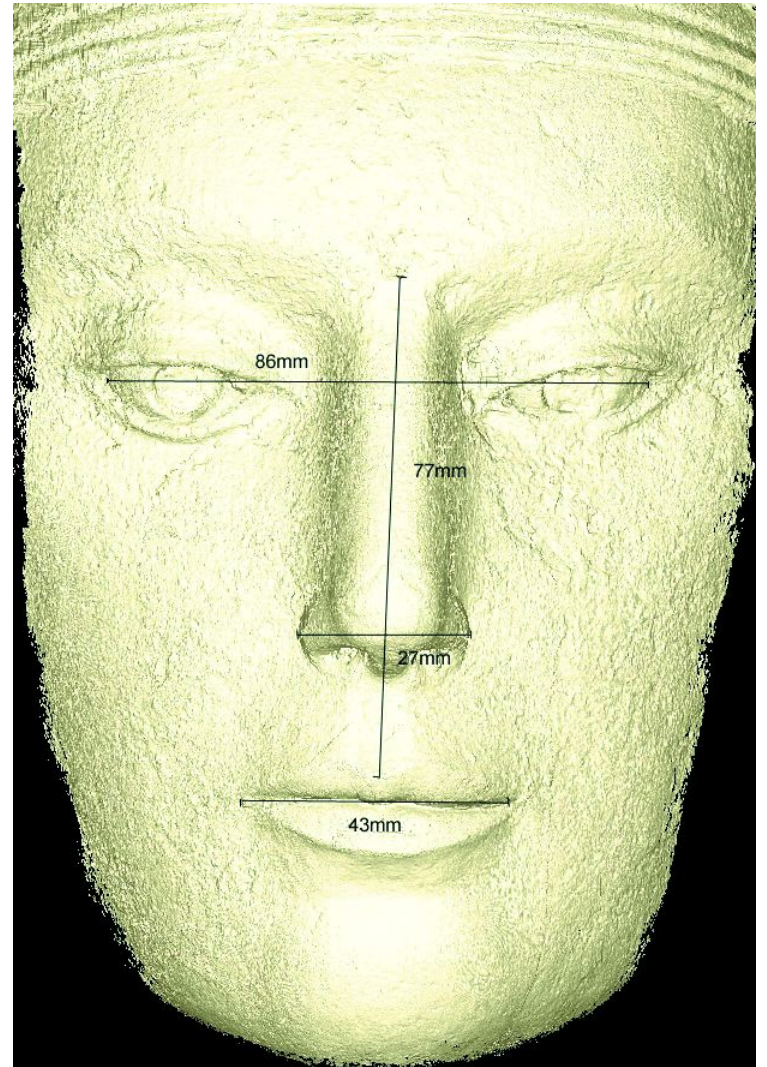
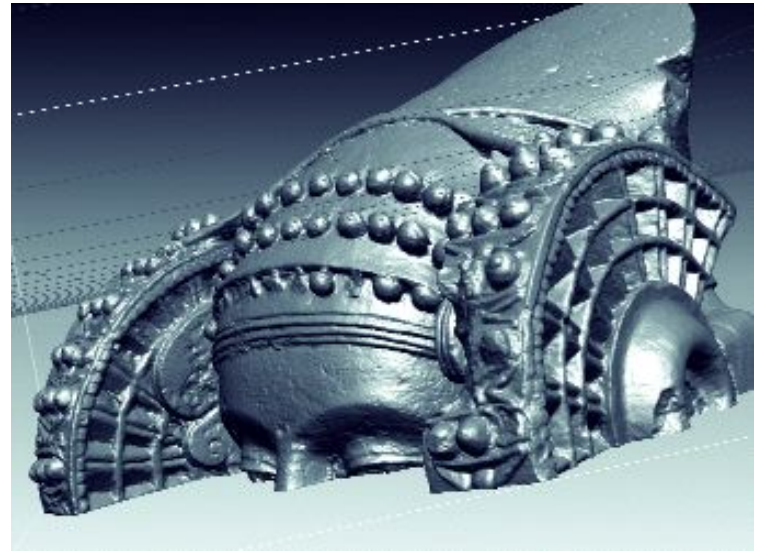


Plate 32

*Data from the Seti Scanner with accurate measurements. This data is essential to monitor surface changes.*





Plates 33 and 34

*Data from the ModelMaker Scanner. In practice the best resolution achieved with the ModelMaker was 100 microns along the scanning line and 250 microns between lines.*



Plates 35 and 36  
*Data from the ModelMaker Scanner*



Plates 37 and 38

*Data from the Minolta Scanner. In practice the best resolution achieved with the Minolta was 170 microns along the scanning line and 250 microns between lines.*

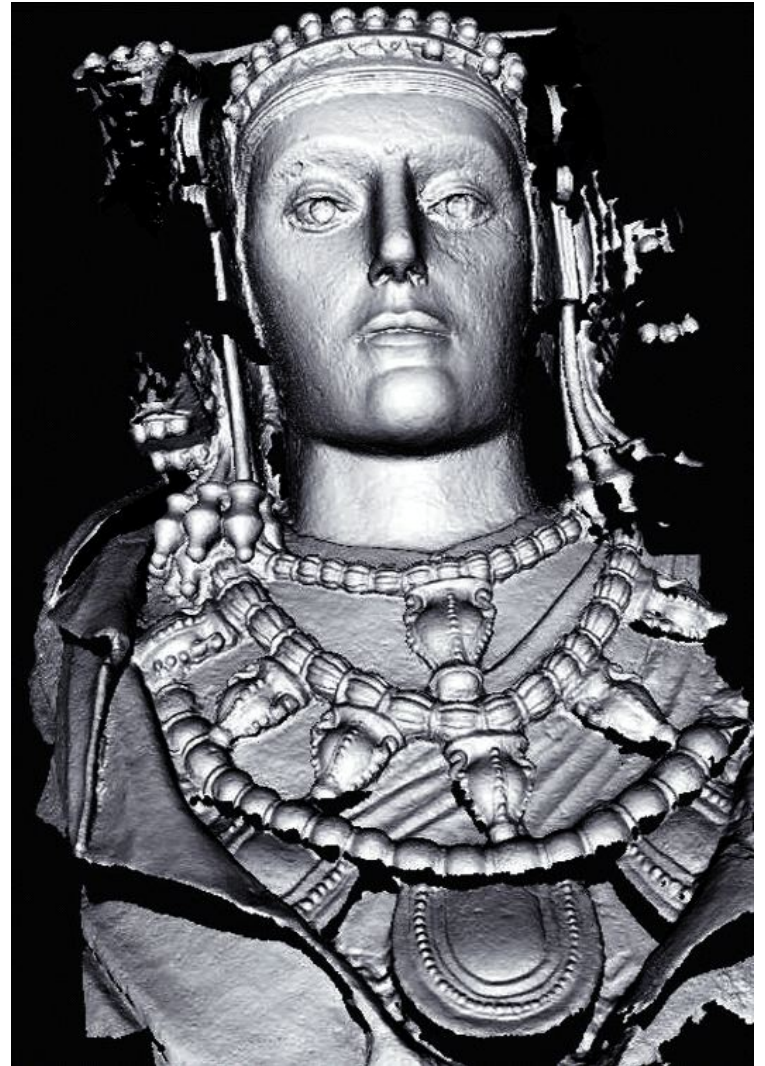


Plate 39

*Data from the Minolta Scanner. The Minolta data contained distortions in the positioning of the 3D points in space that that resulted in its rejection.*



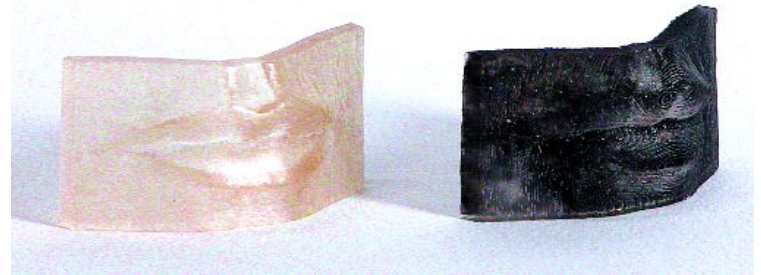


Plate 40

*Two stereolithographic tests of the lips made in transparent resin at different resolutions. Direct comparisons between scanning systems and output methods formed an important part of the research.*

Plate 41

*A close up of lips routed at 100 microns from the Seti Scanner data. Some scanner artifacts are visible which were subsequently removed using specially written software.*

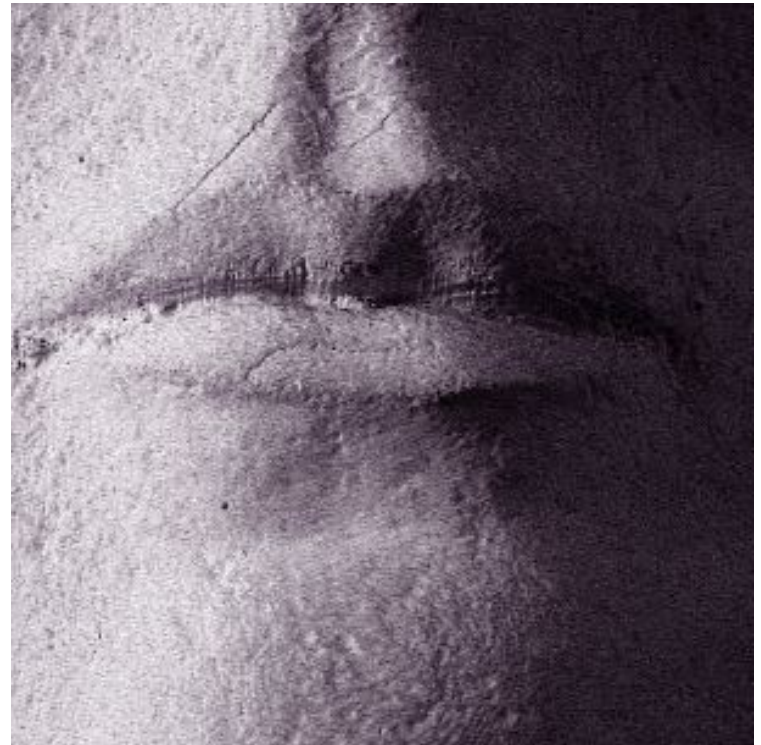




Plate 42

*A test of the Z Corp 3D print made at 100 microns from the Minolta data.*



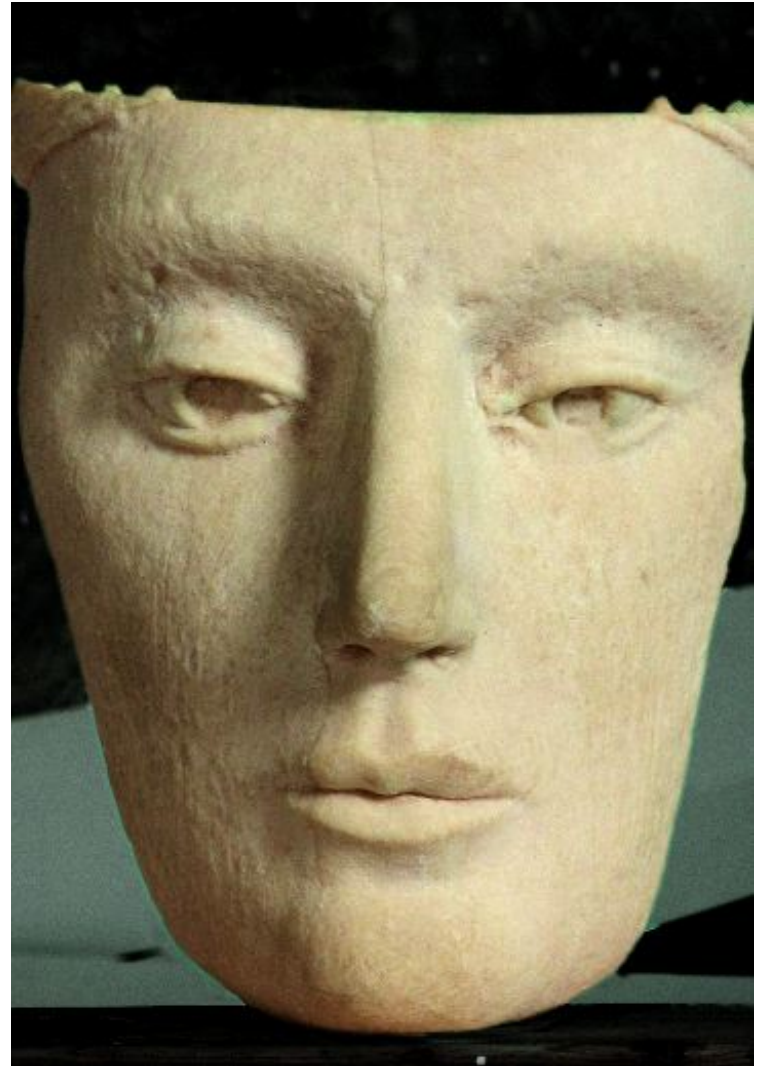
Plate 43

*Routed face from the unmeshed Seti Scanner data.  
The routing was carried out by Delcam UK using a complex routing  
strategy with a final cut of 100 microns.*

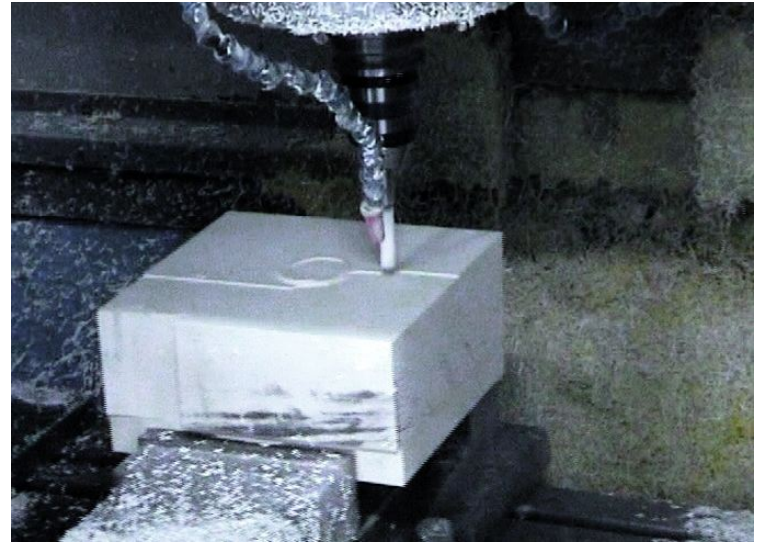
Plate 44

*Z Corp print of the face from the meshed Minolta data.*

*The Z corp print was made in 100 micron layers but compared to the milled data from the Seti Scanner the surface lacks detail and has the appearance of a sucked sweet.*







Plates 45 & 46

*The first stages of the routing of one of the ear pieces. All routing was carried out at Delcam UK using blocks of high density polyurethane.*



Plates 47 & 48

*Each stage of the routing is done with increasingly fine cutting tools. The final pass is with a conical tool with a tip of 100 microns.*

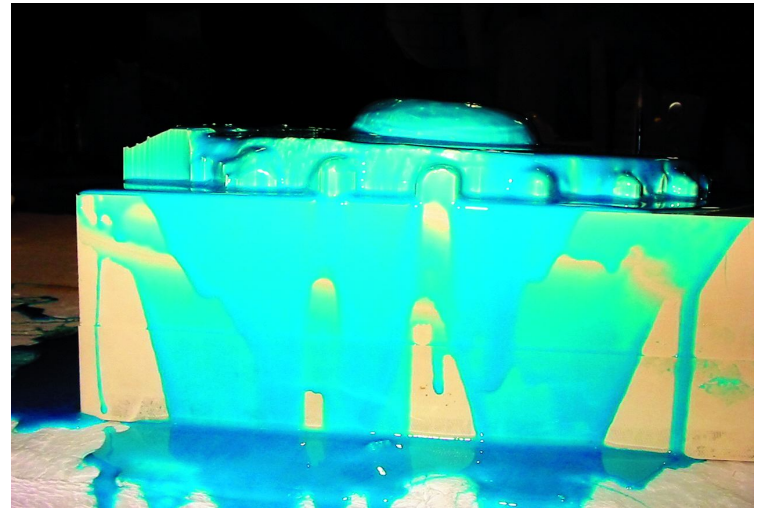


Plate 49  
*The production of silicon moulds from the routed sections.*

Plate 50  
*Casting the routed sections in a mixture of limestone from Elche.  
Resin and pigment.*





Plate 51

*Multiple casts were made to test the different mixtures of limestone and pigment in order to create a surface with the optimum grain size and colour.*

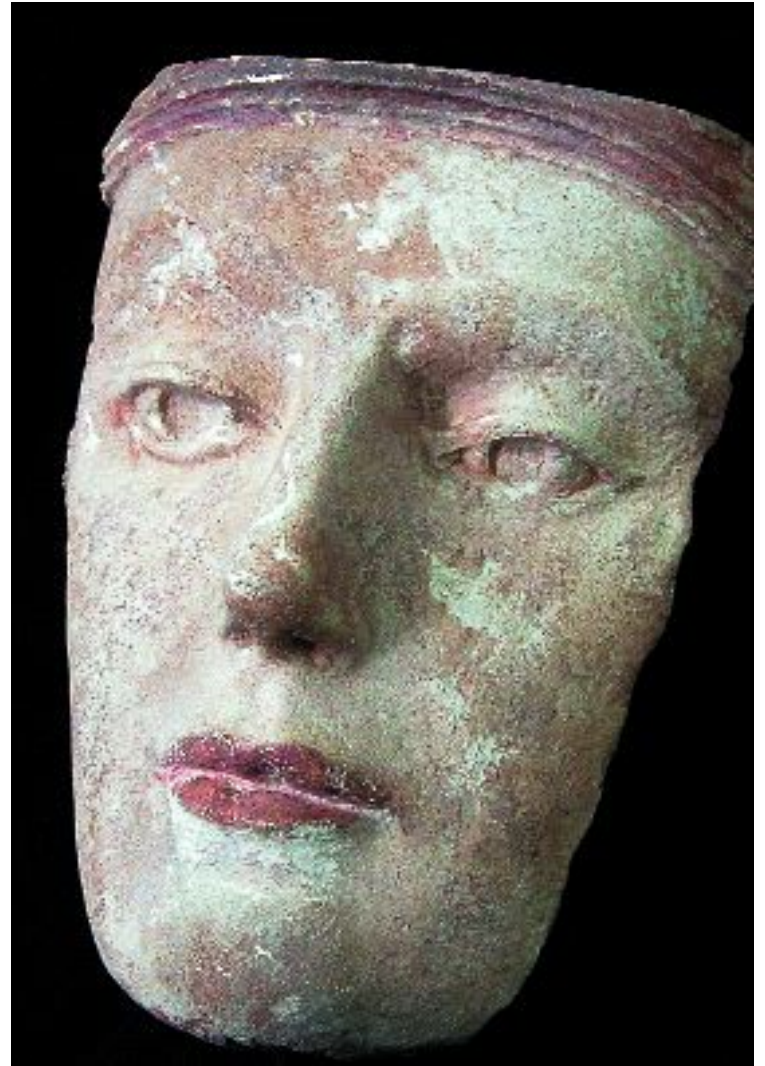


Plate 52

*The first finished test of the face from the Seti data in limestone with pigment. Significant changes were made in the methods of hand finishing following this test.*



Plate 53 & 54

*The first finished tests of the ear pieces from the Seti data in limestone with pigment. Particular attention was paid to the complex layering of the colour.*





Plates 55 & 56

*Two images of the production of the plaster and resin 3D print made using the Z Corp 3D printer in the workshop of 4D Concepts, Germany.*

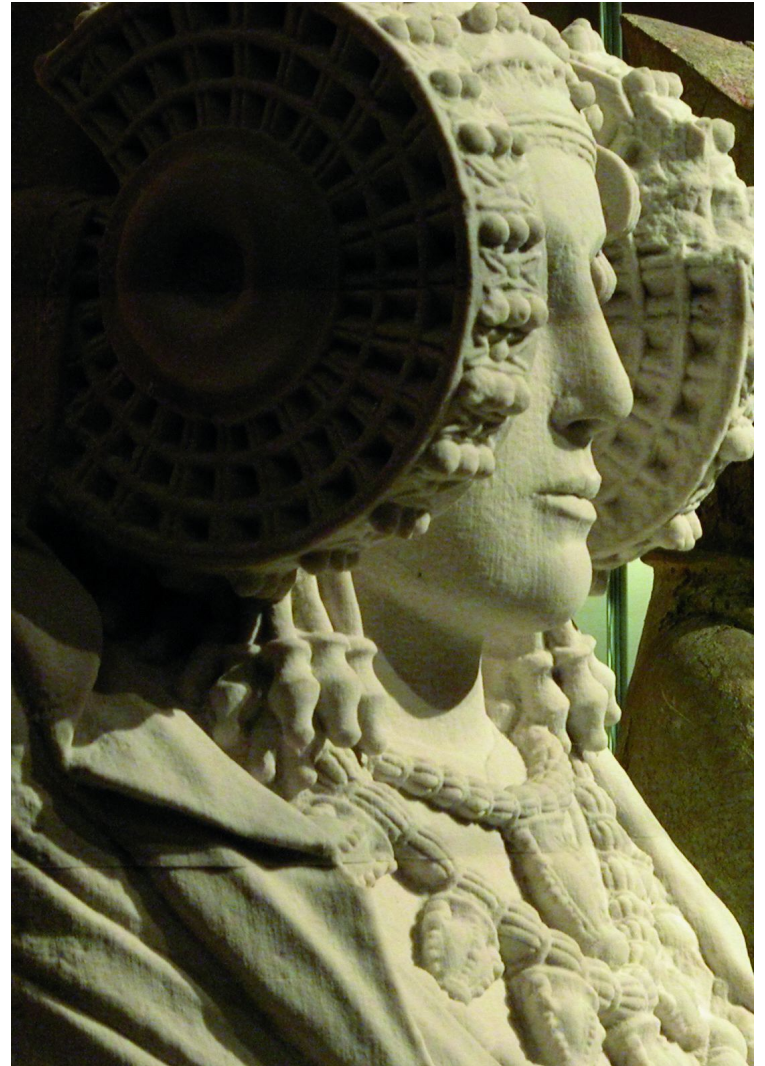


Plate 57

*The finished Z Corp 3D print from the ModelMaker data.*





Plate 58

*The finished Z Corp 3D print from the ModelMaker data. The data was output in 3 sections in layers of 100 microns. The two horizontal joins are clearly visible due to slight changes in colour of each section.*



Plate 59

*The finished Z Corp 3D print from the Minolta data showing the deformations that existed in this data. These deformations can be measured in centimeters not microns.*





Plate 60

*The different data sets were constantly compared and analysed. This focused analysis significantly enhances the understanding of the sculpture.*

Plates 61

*Direct comparisons between the Z Corp 3D prints made from the Minolta data (left) and ModelMaker data (right).*





Plate 62

*A sample of limestone from the quarry in Elche*

Plate 63

*Extensive tests were carried out to create a surface with the same characteristics as the original, particular attention was paid to the way the surface has aged.*





Plate 64

*Applying the first layer of limestone and resin mix tinted to match the internal colour of the stone*



Plate 65

*A selection of tools made by Factum Arte and used during the hand finishing process. These included miniature laser guided airbrushes and sandblasters.*

Plate 66

*After covering with the first layer of limestone the face was coated with latex to protect it while work was done on the rest of the surface.*

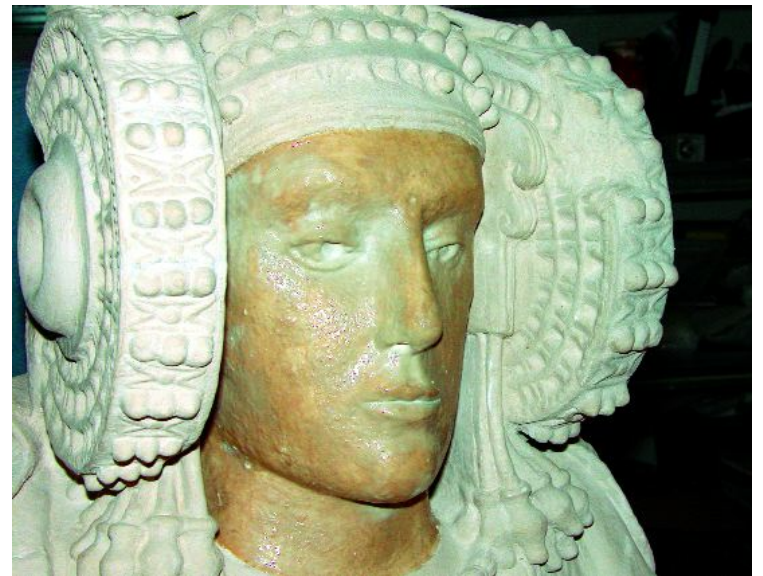




Plate 67

*Applying the layer of limestone and water mix used as a resist to match the surface characteristics of the copy to those of the original.*



Plate 68

*One of the soil samples collected near La Alcudia. This was made into a paste and used to coat the copy.*

Plate 69

*The face of the Sculpture during the removal of the mud.*







Plate 70  
*Coating the copy of the Sculpture with a layer of mud.*



Plate 71  
*Washing the mud from the surface.*



Plate 72

*Heating the surface of the copy to cause the liquid glass layer to crack.*



Plate 73

*Comparing the copy with the original in the museum.*



Plate 74 & 75

*After the direct comparison with the original small alterations were made using tools specially designed for this work. The tool seen here is a miniature sandblaster.*





Plate 76

*Comparing the copy and the original in the museum. The copy was put behind glass to facilitate a true comparison of the colour of the copy with the original in its vitrine.*

Plate 77

*The face of the facsimile. The lips are a rich carmine red and appear to have aged better than the rest of the surface. Further research is necessary to identify if the encrustations are calcium deposits or the remnants of a gesso coating.*





Plate 78 & 79

*Details of both the earpieces. There is clear evidence that the deposits have been raked out of the earpieces. The pigmented areas reveal a complex layering of red and brown colour.*





Plate 80  
*Close up detail of the front of the facsimile.*



Plate 81 & 82

*The base of the sculpture. The traces of the tools used to cut the surface are clearly visible. Similar chisel marks are also visible in the hole at the back of the sculpture. Measurements from the 3D data facilitate an in depth study of these marks.*

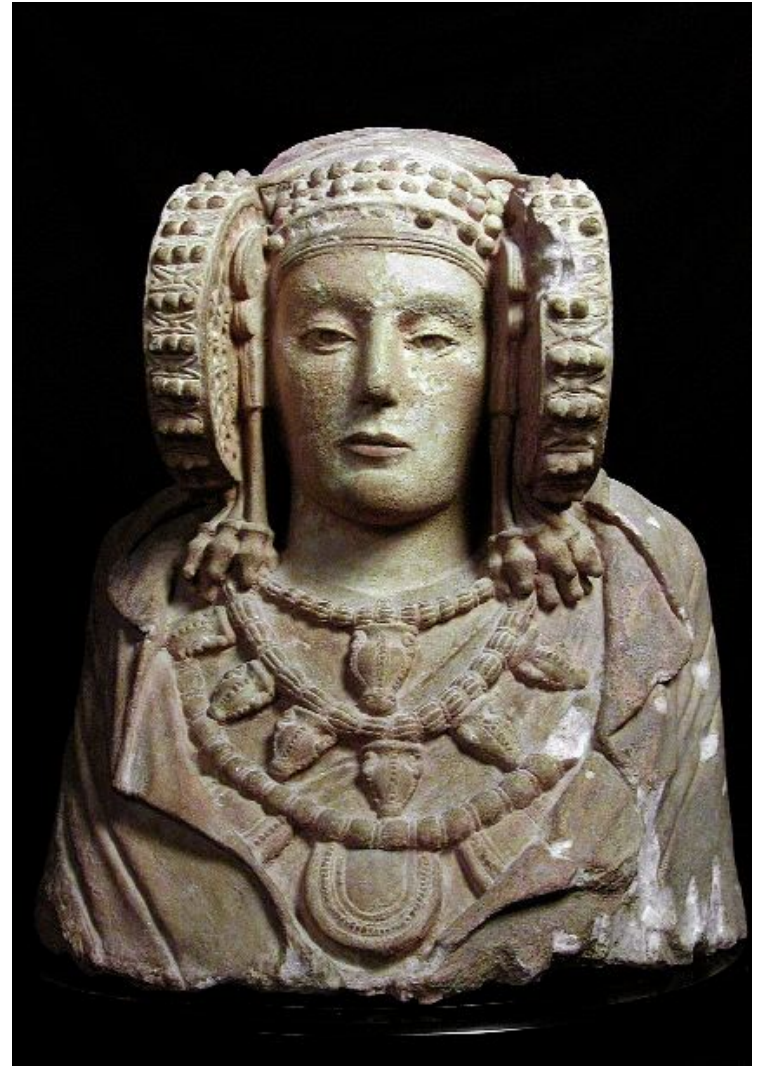


Plate 83

*The finished facsimile in Factum Arte's workshop.*

*Plaster, resin, limestone, mud and pigment.*

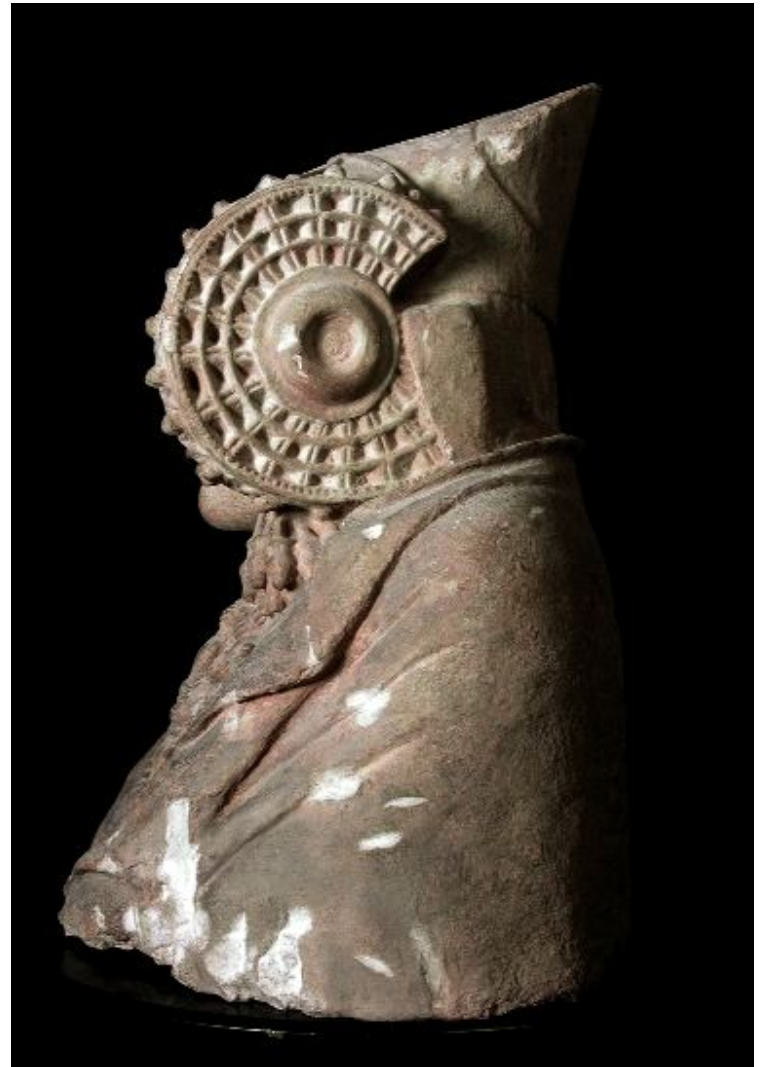


Plate 84  
*The finished facsimile*





Plate 85  
*The finished facsimile*





Plate 86  
*The finished facsimile*