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The Qaitbay Underwater Site at Alexandria, Egypt: The evolution of surveying techniques

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The underwater site of Qaitbay has been studied by the Centre d'Études Alexandrines (CEAlex) since 1994. The vast majority of the pieces have been catalogued and studied, initially using traditional techniques. In 2009, the CEAlex integrated certain trans-disciplinary specialities, including digital humanities and, within this, photogrammetry. Our motivation sprang from issues with the study of underwater fragments of ancient sculpture and architectural blocks. With the support of the Honor Frost Foundation, the CEAlex became fully involved in photogrammetry in 2013, mastering the techniques and inventing an innovative means of data acquisition in a situation where more modern methods such as side-scan sonar had failed.

Key words

Underwater archaeology, Alexandria, lighthouse, photogrammetry

The underwater site is located in Alexandria, Egypt, north of the medieval fort built in 1477 by Sultan Al Ashraf Seif el Dine Qaitbay (Fig. 1). Tradition places the foundations of the old Pharos of Alexandria[1] under the keep of the Mamluk fort, while the underwater excavations locate it some dozen metres northwest of the

[1] The lighthouse construction began in the early third century BC by Ptolemy I Soter (305–283 BC) and was completed by his son, Ptolomy II Philadelphus (283–246 BC) about fifteen years later.

keep, on a now submerged islet which formed the eastern point of the ancient island of Pharos, the end of which emerged from the littoral Holocene ridge that closes to the north the two great Alexandrian ports in a discontinuous line of reefs and islets. Subsidence, in a combination of natural phenomena, is the cause of the disappearance of the islet of Pharos (Papatheodorou *et al*, 2015, 27–61) which rose at least 2m above sea level 23 centuries ago, when the lighthouse was built there. Today it is submerged 5m below sea level, as are the coastal constructions of the ancient city.

Archaeological investigations carried out since 1994 by the Centre d'Études Alexandrines (CEAlex), running one to two campaigns per year, have produced a large number of indications that corroborate the historical data and ancient iconographers who described the old lighthouse, offering the most secure location of the missing monument (see Empereur, from 1995 to 2004; and Guimier-Sorbets, 1997; Hairy, 2004; Hairy, 2007; Hairy, 2016). The site is large, which presents one of the greatest problems. Geographically, it covers more than 3 hectares of dune sandstone (calcarenite) and sand. The visible part of the 3032 blocks[2] listed in the database at the beginning of 2017, lying at depths between 2.60m and 9m, extends over an area of 13,000m^2 (Fig. 2). There are various constraints to the study of submerged finds: the difficulty of access to finds under water, visibility issues, pollution, and difficulties related to the weight of the blocks, the heaviest being more than 40 metric tons. The raising of 36 architectural and statuary elements (out of a total of 3500 detected underwater, so just 1% of the submerged ruins) carried out between 1995 and 1999[3], quickly demonstrated the limits of such an operation. Access to this underwater cultural heritage, among the richest of ancient Alexandria, is not ideal, although some monuments have been raised and have enhanced the ancient heritage of the modern city (Fig. 3).

Through this brief presentation, we will demonstrate the importance of such a site for Alexandrian and Egyptian heritage, since the Pharos of Alexandria is at least as famous as the pyramids of Cheops and Kephren! But it is important to recognize that the difficulty of access to the underwater site makes its visibility to the general public practically zero, except through images, photos published in mainstream journals, and documentaries which quickly become obsolete as the work of archaeologists progresses.

The development of surveying techniques

Let's begin by looking at how the site was set up for study from 1994. The understanding of such a vast site involved the creation of an inventory of all the elements within it: ancient blocks, other artefacts, reliefs, as

[2] This corresponds to a mass of approximately 5256 tonnes of imported rock, of which 76.09% is granite.
[3] In 2000, the Egyptian Antiquities Service decided that it no longer wished to authorise the lifting of finds weighing more than 100kg. The Supreme Council of Antiquities did however make an exception for the right hand of a statue in 2001, which was raised in order to be returned to its body as part of the European research programme Médistone. It was replaced on the colossus which represents one of the first two Ptolemy's and is today displayed in front of the library at Alexandria.

well as locational maps. The general plan of the site (Fig. 2) was created using different methods of topography, traditional and modern. Until 2001, surveys were carried out by triangulation, the only method that can be used in heavy weather, but also by direct topography using an underwater adjustable cord bearing a 35-kilo weight with a pointer at the end attached to a buoy on the surface. The buoy is fitted with a reflective prism (used for long distance measuring) and there is an electronic theodolite on shore to take the measurements (Fig. 4). This last method is particularly efficient on the Qaitbay site because of its shallow depth – between 3.5m and 9m – and because of its proximity to the shore[4]. However, there is a major drawback: it can be used only in very good weather, without any swell moving the buoy on the surface, and without currents that displace the buoy from a position directly above its anchoring point on the seabed. Although the method has been abandoned to plot the position of the ancient blocks, it has nevertheless been retained to orient the site with the general coordinate system of mainland Alexandria, by means of reference points. The map of the underwater site thus connected to the general topography of the city[5] was integrated into the Alexandria GIS developed by CEAlex (Ablain, 1995; Fadin, 1996).

In 1998, the orthogonal grid system was set up on the site using a metal frame of 6m x 6m, divided into 1m squares and mounted on adjustable feet, which has accelerated the survey of large flat areas of the site cleared by the lifting of the submerged modern seawall. This method allowed for the optimisation of the underwater survey time of these large areas with a very high concentration of archaeological material. However, the process could not be used on surfaces differing by more than 1m in height[6].

In 2001, a more modern method made it possible to optimise the topographical work with a tool adapted to the aquatic environment. This is the Aqua-metre D100[7], an underwater acoustic survey device that works on the principle of sound transmissions that can record the precise location, in three dimensions, of submerged objects, through the measurement of angles and distances. The device consists of a fixed receiver base and a hand-held pointer-emitter in which the relative coordinates are stored (Fig. 5); measurements can be taken within a radius of 100m from the base[8]. This instrument is a huge advance compared to the methods used previously: it can be used during any type of weather. The topographic points taken under water are loaded directly into a computer and feed the GIS map directly. The tool does however have some major disadvantages: the conditions of optimal use include the absence of noise interference (surf, divers in the proximity of the base, boat engines, etc.), since it works by means of the propagation of sound in the water, and the absence of masks between the pointer and the base (divers, fish, etc.), otherwise it will record

[4] The theodolite can only take measurements less than 500m from the shore.
[5] The CEAlex building is permanently equipped with a GPS station, installed in 2001.
[6] On this surface of about 600m^2 cleared by the removal of concrete blocks, 326 blocks were mapped during the two annual campaigns (Hairy, 1998a, and 1998b).
[7] The fine-tuning of the first version of the acoustic device, the Aqua-metre D100, developed by PLSM Instrumentation (www.plsm.eu) was carried out in 1999 during the Qaitbay underwater excavation.
[8] Today, the same device has a range with a radius of 150m.

abnormal measurements. In the end, the team-divers are still required to plot the position of the base receiver and of the reference points within the general coordinate system using direct topography.

The creation of the site map was coupled with the inventory of the mapped items. Each block was documented, described in minute detail, drawn, and photographed (Fig. 6). The data were recorded in two databases: the cartography in the GIS developed in MapInfo[9], and the inventory of finds, including descriptive forms and multimedia data, developed in FileMaker Pro.

The databases serve in many ways for the study of the site, but also for the management of the site and the organisation of the work of the divers. For example: in certain areas of the site, the blocks are piled up in several layers, so it is necessary to remove the upper layers once their recording is completed in order to reach the lower layers. To do this, we use lifting straps and balloons to carry the blocks into the underwater collection areas where they will be stored (Fig. 7). These actions were managed through GIS. As a preliminary, the weight of each piece was calculated using the information contained in the form about the block: this information made it possible to quantify the volume of balloons necessary for the different planned movements on the morning of a dive.

Alongside this systematic recording, specialised studies were initiated on particularly remarkable blocks selected from the inventory: inscriptions, decorations, metal finds, imported rocks, geomorphology of the substrate, etc. The substrate can be observed through archaeological exploration of the sandy areas; the excavations make it possible to measure the altitude of the calcarenite substratum and to determine the zones suitable for excavation while also exposing fragments of blocks or lead seals.

A large number of lead objects and some in bronze or iron have been discovered on the site. Seals made of lead or lead and iron are the most numerous; 65 of them have been brought to the surface since the beginning of the excavation, a mass of about 160 kg of metal, mostly dowel type architectural seals or clamps from the assembly of the ancient blocks discovered on the site. A remarkable piece – a dovetail joint in the shape of a π weighing nearly 20 kg – was used to hold one of the two uprights of the monumental Greek-style doorway found on the site. Two other pieces, exceptional because they were made of almost pure iron – 91% iron for the door knocker and 95% for the door hinge – were probably part of the ironwork on this same monumental doorway. The false hinge strip held the frame and friezes of a door leaf that was more than 9cm thick. Thanks to the restoration of the doorway in granite (Hairy, 2007), the volume and weight of a door leaf could be evaluated: in cedar wood, this leaf would have weighed nearly 1.5 metric tons.

9 The data will be transferred to QGIS, a free and open source geographic information system, downloadable from the internet.

The databases inform us about the importance of the items to be studied, and the management of the site through GIS makes it possible to locate them underwater. These finds are the subject of a detailed survey. The study of the complex architectural blocks, statue fragments, inscriptions, and decorations is particularly challenging in an underwater context. For the inscriptions and decorations on flat surfaces, moulds[10] were taken. The accuracy of the copy has often made it possible to read texts, and sometimes to analyze the decorations. Although the technique of silicone moulding gives very detailed results, it is only capable of reproducing part of the block and thus limits its analysis.

For architectural blocks, whole or fragmentary, detailed surveys have led to the reconstruction of some monuments or parts of them. The complexity of certain re-assemblies or reconstructions has once again encouraged innovation in data acquisition techniques, both for ancient finds and for the site itself, whose extent and rugged geometry make analysis complex. In 2009, as part of the ANR[11]-SeARCH[12] programme (Reuters *et al*, 2011), a collaboration was initiated between heritage experts and computer scientists, bringing together four partners: Estia-Recherche (Biarritz) for interaction techniques between humans and computers and surface reconstruction; 3D Archeovision (Bordeaux) for techniques of 3D reconstruction of cultural heritage; INRIA[13]-IPARLA (Bordeaux) for geometric surface modelling, the interface with the users, and the manual virtual assembly of fragmentary archaeological objects; and finally CEAlex for its expertise in cultural heritage and data acquisition. Our motivation was driven by the difficulty of studying fragments of ancient sculpture and architectural blocks under water, due to the complexity and risks associated with physical analysis given their size and weight, and the difficulty of access and bad lighting conditions, as well as surface erosion after centuries of submersion. Our aim was to find a simple and inexpensive, and non-polluting method that was adapted to both underwater and terrestrial contexts.

Photogrammetry was quickly chosen due to the quality of the results, its practical application and its low cost. Initially, the programme focused on creating digital copies in 3D of the finds, resulting, in 2010, in a virtual library (Hairy *et al*, 2016). A unique acquisition method has also been developed both for recovered finds, thus in the terrestrial context, and for finds still under water. This issue was crucial since we knew we would have to virtually re-assemble fragments that were in both types of context. In 2012, at the end of the ANR SeARCH programme, CEAlex took over the Qaitbay underwater photogrammetry project with a team that today consists of four people: Mohamed El Sayed, CSA underwater archaeologist; Mohamed Abd el Aziz, CSA archaeologist and photogrammetry specialist; Philippe Soubias, CNRS-CEAlex photographer; and

[10] Most of the moulding work was carried out in 1999, under the direction of Georges Brocot, who at the time was the director of the DRASSM-Annecy laboratory for moulding and freeze-drying and a conservator specialising in underwater castings. He is the inventor of the underwater silicone and resin casting technique used on the submerged finds of the Qaitbay site.

[11] Agence Nationale de la Recherche
[12] Semi-automatic 3D Acquisition and Reassembly of Cultural Heritage
[13] Institut National de Recherche en informatique et en automatique

myself. The team worked on perfecting the protocol for the acquisition and treatment of finds, in particular to improve the quality of the virtual reconstruction.

To illustrate the development of our work, I present here an example of reconstruction work on the colossal statue of Queen Isis, from the 2001 drawing to our virtual anastylosis results completed in 2015, after the collection, in 2011, of a complete set of photos of the two main fragments of the statue preserved in the gardens of the Maritime Museum in Alexandria, and the acquisition by us, in 2015, of the crown kept in the open air museum of the archaeological site of Kom el-Dikka[14] (Fig. 8).

The semi-automatic re-assembly programme developed by the INRIA-IPARLA computer scientists could not solve the issue of the assembly of the two fragments of the body of the statue. Our team achieved this by reprocessing the fragments in order to obtain a cleaner 3D model, with sufficient textural detail, and taking great care with the processing of the scale of the fragments, essential for the accurate reconstruction. We also learnt the importance of manual re-assembly work, where the eye of the expert can reconstitute, thanks to his or her knowledge of the subject, the missing and eroded parts. The re-assembly of the fragments and the reconstruction of this statue are now solved based on properly handled photogrammetry and the management of the reconstruction by heritage experts.

With the completion of the virtual anastylosis, the statue can be studied in the laboratory through 3D expressive visualizations; this means finding the best 'virtual lighting' to highlight the characteristics of sculpture. Virtual anastylosis and the study of volumes and surfaces were conducted using the Meshlab programme, free software for 3D grid processing, developed by ISTI[15] and CNR[16], offering a simple tool for the handling and editing of 3D models, widely used in the field of research and cultural heritage management. 3D models are produced in Agisoft Photoscan, a software that uses automated photogrammetric image processing technology. The 3D models, created from Photoscan or after anastylosis in Meshlab, embed a third software, Sketchup, a 3D image creation software for modelling, where the reconstructions of the missing parts are carried out, and the architectural forms virtually reconstructed. In these virtual spaces, the copies of the blocks are placed in a landscape, testing colours, textures and lights with different shades, using a range of different viewpoints.

New initiatives and future challenges

Thanks to the sponsorship of the Honor Frost Foundation, which has been part of this project since 2013, the team launched, in 2014, in a new initiative: a 3D Digital Surface Model (DSM) of the site. In 2017 nearly 8000 m^2 of the DSM were created (Fig. 9). The method for carrying out this project has been proven, the

14 A virtual tour of the Roman Theatre open-air museum is available at the following address: http://www.cealex.org/sitecealex/navigation/FENETR_NAVfouil_smarin_F.htm
15 Istituto di Scienza e Tecnologiedell'Informazione
16 Consiglio Nazionale delle Ricerche

scaling of the pieces of the puzzle for the DSM has been successful, and the question of geo-referencing has been solved; we still have some adjustment issues to deal with, and of course to finish the rest of the site.

Once this work has been completed, we can consider ways of extracting scientific information from this documentation, such as the creation of a Digital Terrain Model (DTM), i.e., the geography of the substratum on which the ancient blocks sit. Ideally, the DSM and the DTM will be linked to different databases that store all the information collected since the beginning of the project in 1994.

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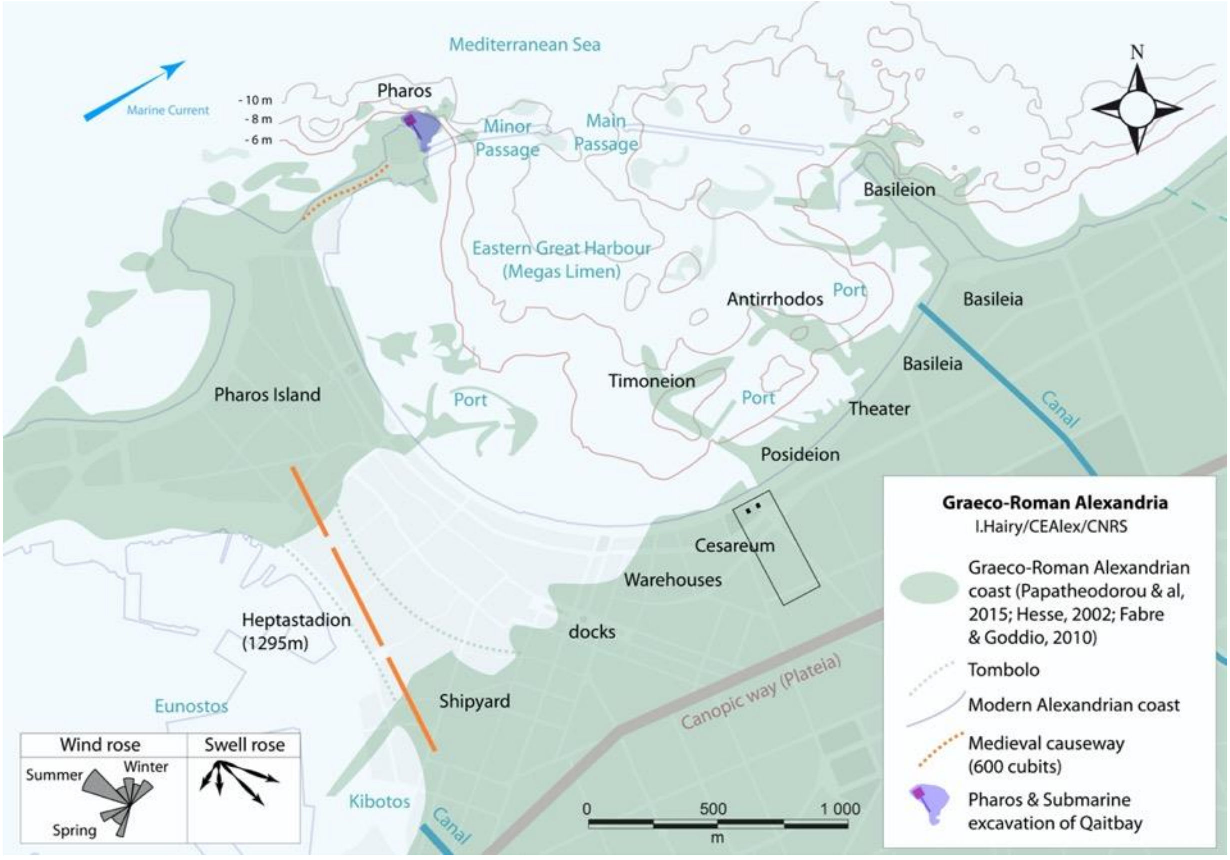
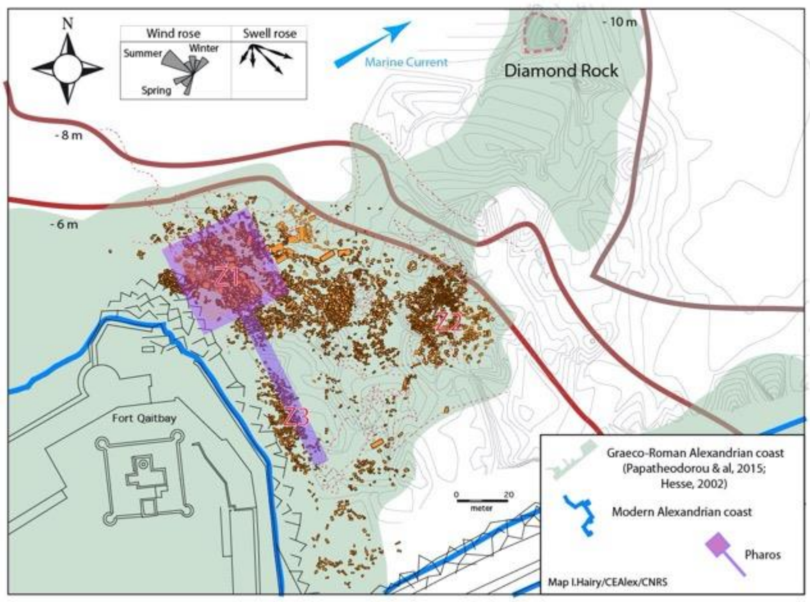


Figure 1. Position of the site on the Alexandrine coast (map by I. Hairy).



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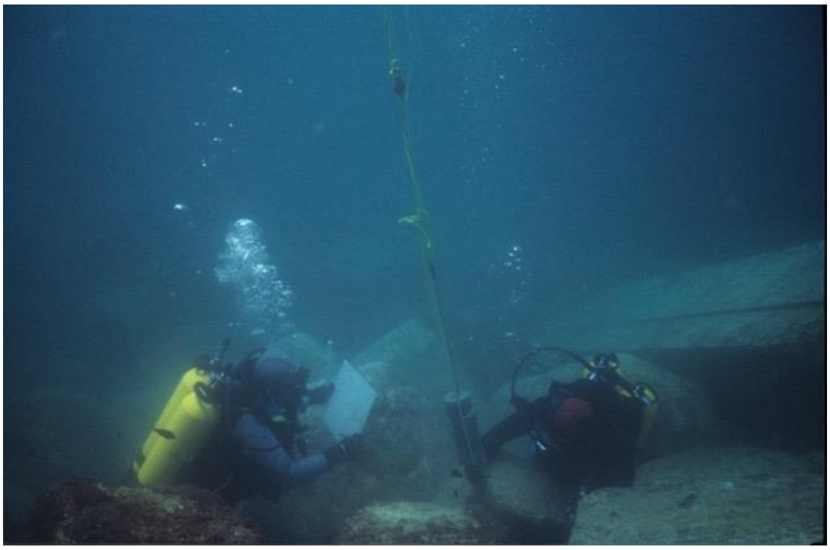

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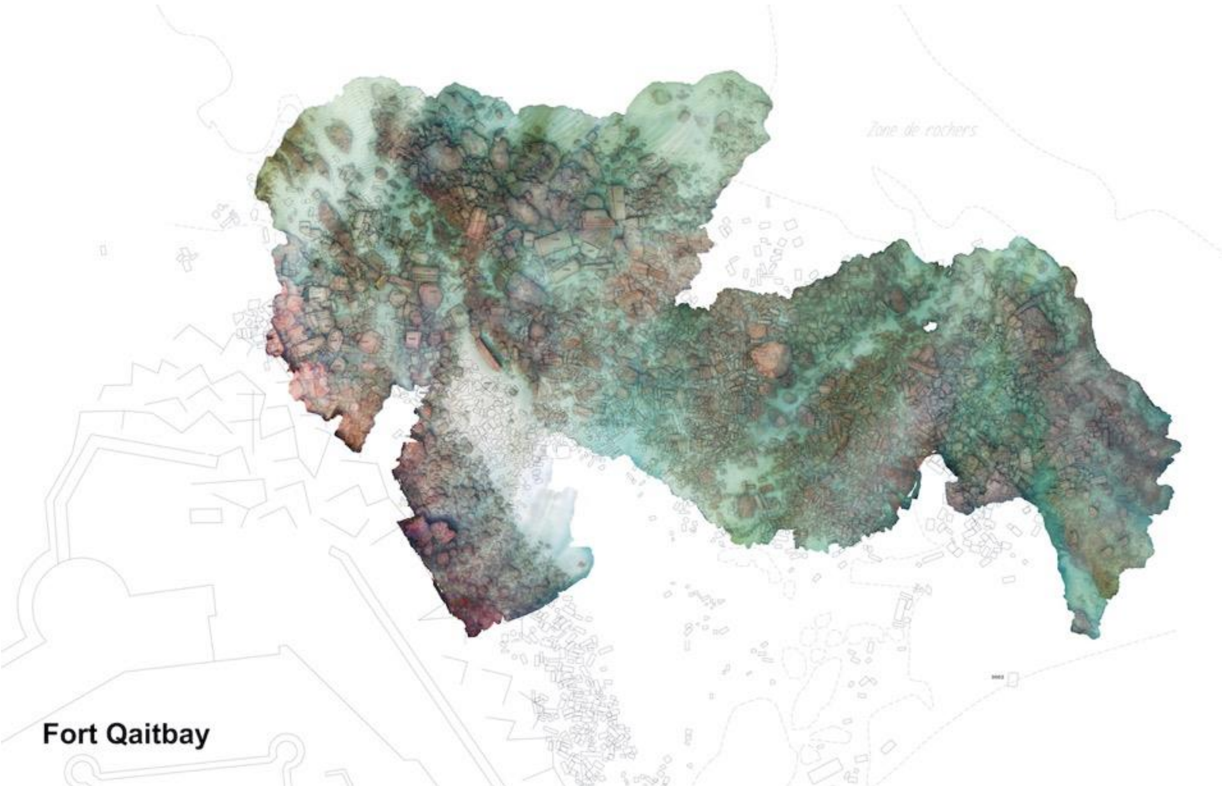

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