CAESAREA Papers 2.
JRA Suppl. 35

Pozzolana, lime, and single-mission barges (area K)

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with **Stephen Kemp and Martin Grove**

Area K, an area of 35 x 70 m at the N end of the main southern breakwater of the Herodian harbour (frontispiece and fig. 1), includes the remains of the "twin towers" referred to by Josephus (*BellJ* 1.413). The main part of area K lying south of these towers comprises a tumbled mass of kurkar[1] and concrete blocks that rise from the sand- and rubble-strewn seabed at a depth of -7 *m* to -2 *m*. Under and within this chaotic pile are the remains of 5 concrete-filled timber caissons, each 7 x 14 m in plan and 3.5 to 4 m high, laid out across the seabed in a loose header arrangement on a N-S line (fig. 3). K2 lies 5 m to the south of the "twin towers" and runs nearly E-W. The array of blocks lines up with the end of the N breakwater and originally formed the foundation of the sea wall that protected the W side of the entrance channel.[2]

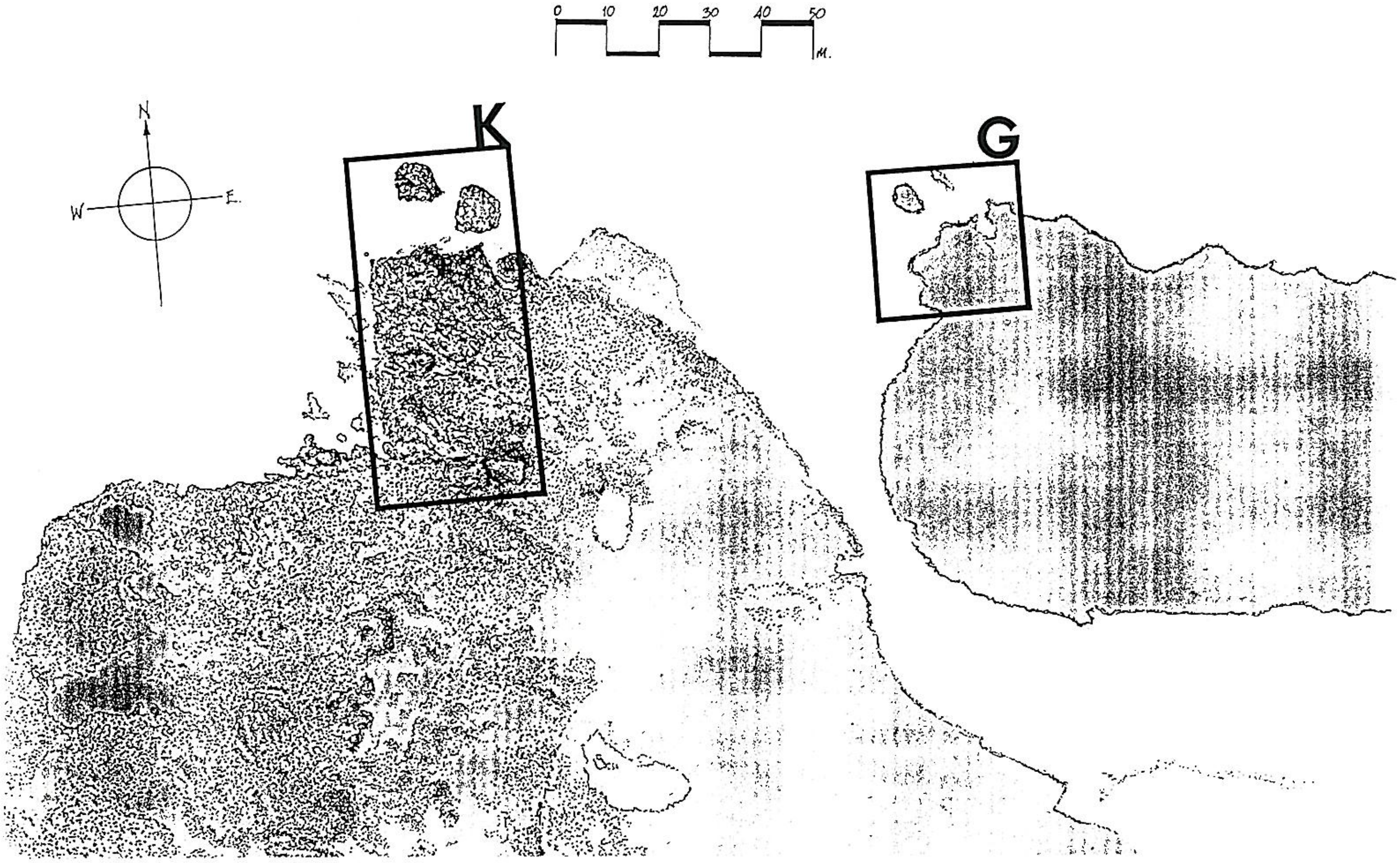

Fig. 1. Site locations of areas G and K (cf. frontispiece) (C. Brandon).

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[1] Kurkar, the local building stone, is a relatively soft and porous carbonate-cemented quartz eolianite sandstone; see J. P. Oleson and G. Branton, "The technology of King Herod's harbour," *Caesarea papers* 58-63.

[2] R. L. Vann, "The Drusion: a candidate for Herod's lighthouse at Caesarea Maritima," *IJNA* 20 (1991) 123-39, suggests that the tumbled mass of kurkar and masonry blocks in area K is the remains of a lighthouse, perhaps the Drusion tower that Josephus mentions. The arrangement of the blocks, however, which are set out of line, suits the pad stones of a sea wall better than the foundation of a tower.

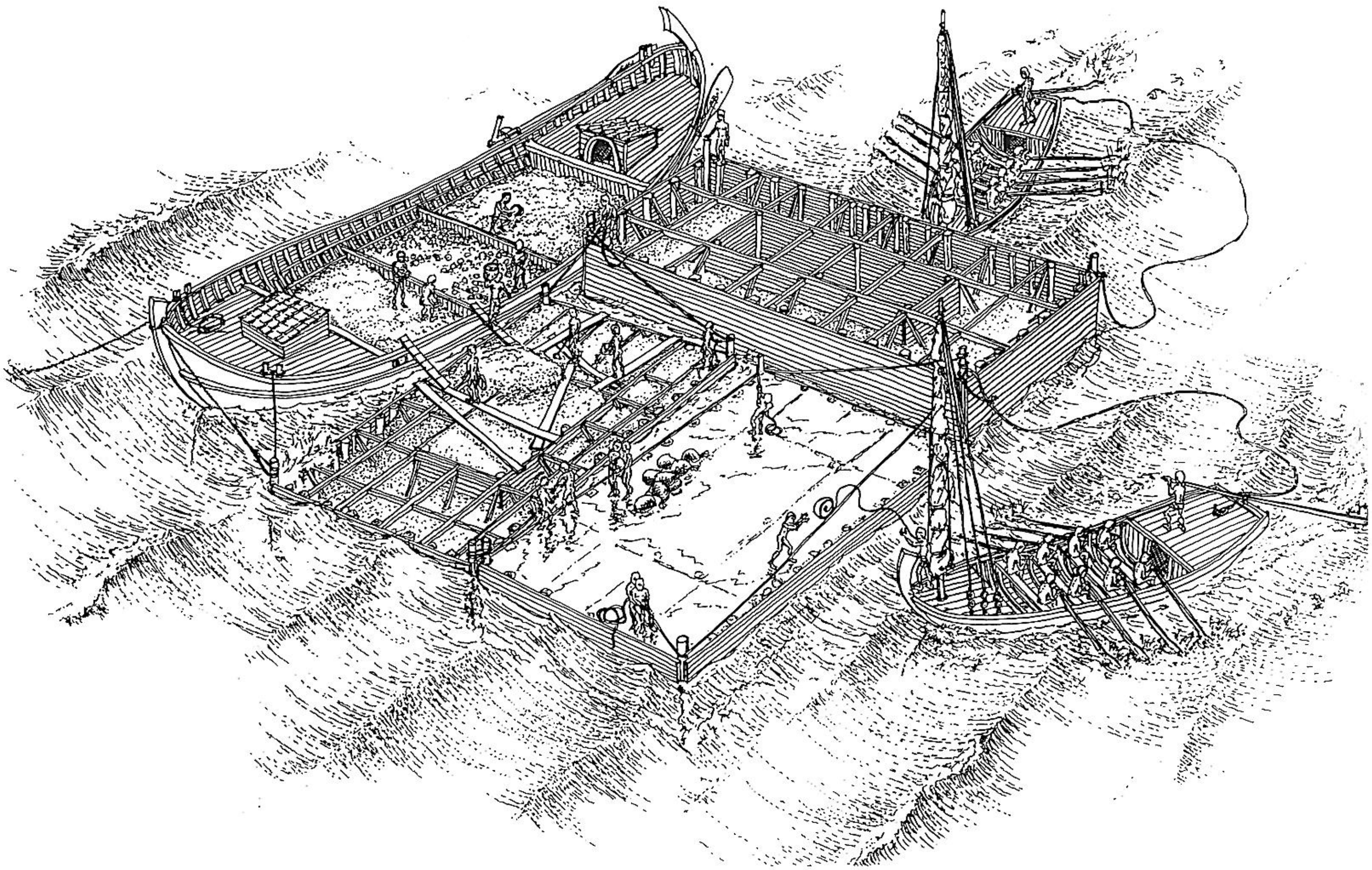

Fig. 2. Reconstruction of area K caissons being filled with concrete and sunk (C. Brandon).

The design, construction, and quality of the blocks varied greatly and were not consistent. The timber formwork within which the concrete was cast consisted of an elaborately-constructed watertight box. The concrete fill, however, was inherently flawed in that it had a central core that was considerably weaker and softer than the surrounding layers.

The meticulously and laboriously crafted timber caissons, or single-mission barges, illustrate the extraordinary effort that went into construction of the harbour. Substantial remains of the timber preserved under the seabed permit a detailed hypothetical reconstruction (fig. 2).[3] The rectangular caissons measured 7 x 14 x 4 m, and the exterior shell was reinforced by bracing. At least one caisson, K2, had a central cell (fig. 2). All were constructed with planking that was fastened at the edges with mortises and tenons transfixed by treenails in the same manner as traditional shell-first ship construction. This method of fixing the boards was used not only on the sides and bottom but also to form the inner compartment. There is no evidence of any caulking material between the boards but the quality and method of construction leads one to believe that the caissons were watertight. The builders used chine beams to form the junction between side walls and the floor to achieve the rectangular shape necessary for setting block against block and to ensure uniform distribution of the overlying loads (fig. 4). As in a ship, floor and side-wall frames, made of rough-hewn pine sections, were fixed to the boards with treenails. They strengthened the shell and transferred the hydrostatic loads to the internal framing and diagonal bracing. The corner posts that formed the rectangular plan were rebated

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[3] C. J. Brandon, ""The concrete filled barges of King Herod's harbour of Sebastos" in *6th International Symposium on Ship Construction in Antiquity, Lamia, Greece 1996* (Tropis 6, in press).

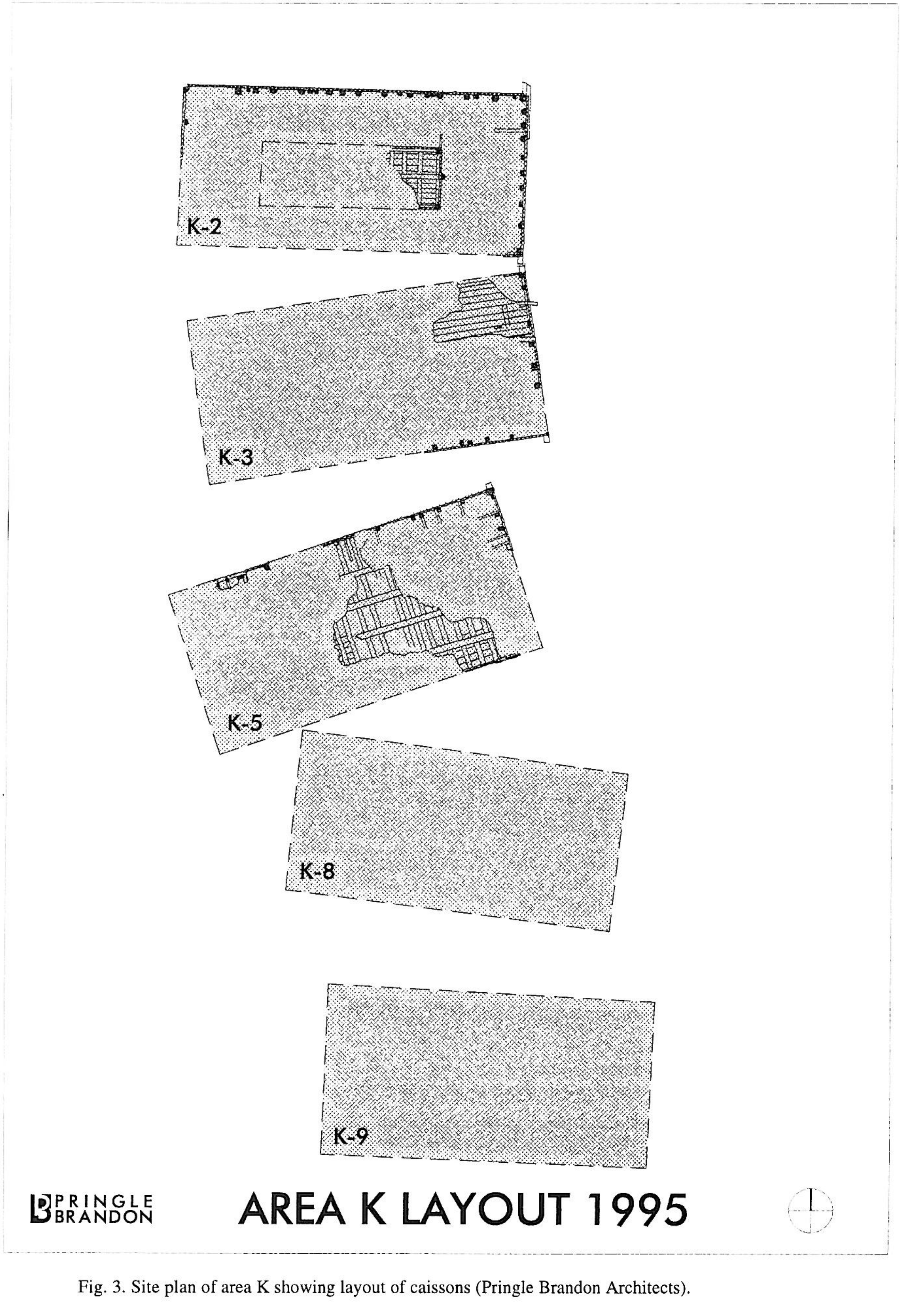
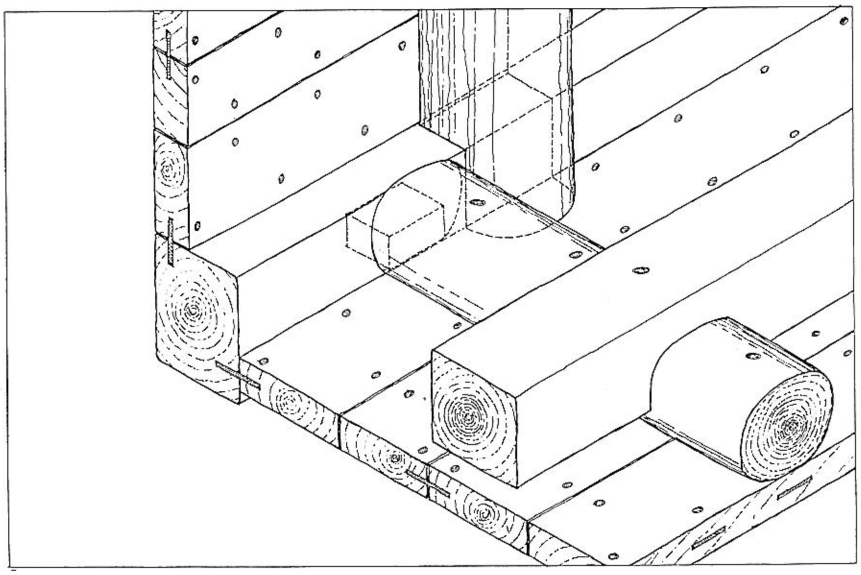


Fig. 3. Site plan of area K showing layout of caissons (Pringle Brandon Architects).



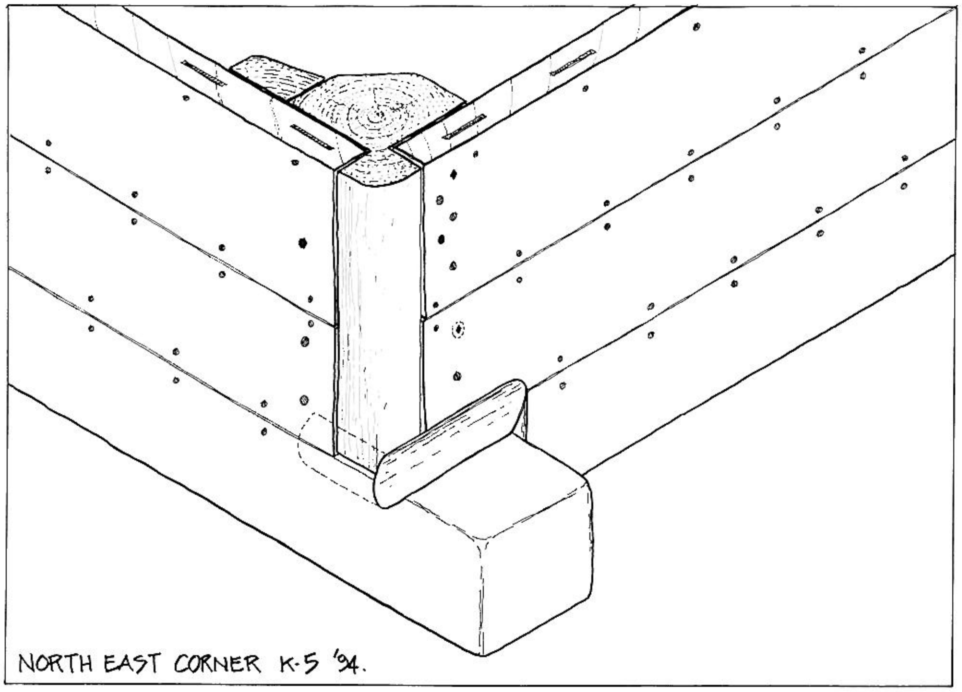


Fig. 4 (top). Detail of chine beam of area K caisson (C. Brandon).
Fig. 5 (below). Detail of caisson corner in area K (C. Brandon).

to allow the ends of the boards to be let in on either side of the post, and the boards were fixed in place with a combination of metal pins and treenails (fig. 5). The timbers used in the construction of these caissons appear similar to those used in the caissons found in area G, notably spruce, pine, fir, and poplar, all of European origin and imported.[4] Each barge was built of *c.*64 m^3 of wood weighing 32 tons.[5]

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[4] J. P. Oleson, "Herod and Vitruvius: preliminary thoughts on harbour engineering at Sebastos, the harbour at Caesarea Maritima," in A. Raban (ed.), *Harbour archaeology* (BAR S257, Oxford 1985) 168.

[5] This estimate is based on overall size and known construction of the caissons. The floor consisted of 7.8 m^3, the outer walls of 13.4 m^3, and the inner cell 6 m^3, totalling *c.*27 m^3. In addition, there was *c.*37 m^3 of

The Roman engineers who designed and built the harbour were well versed in the use of concrete for the construction of structures within the sea. The harbour at Cosa, which had concrete piers cast underwater in the sea, was built in the first half of the 2nd c. B.C., over 100 years earlier.[6] Vitruvius, writing contemporary with the founding of the Herodian harbour, describes the making and use of hydraulic concrete.[7] Roman concrete differed from modern concrete not only in its chemical make-up but also in the manner in which it was placed. Roman concrete was a lime and sand mortar, into which large lumps of aggregate *c.*100-300 mm in length were individually placed by hand to build up its mass layer by layer. For increased strength and for hydraulic purposes, volcanic sand (*pozzolana*) was added to the mix, as well as crushed pottery or tiles. Modern concrete, on the other hand, is a mixture of cement (an amalgam of lime, clay, and metallic salts) combined with a fine aggregate, usually a sharp sand, and a coarse aggregate of crushed stone *c.*25 mm in diameter. In modern practice, unlike in the Roman period, the ingredients for the concrete are all mixed together dry before water is added and the material poured into the formwork. Like the timbers, the raw material for the hydraulic concrete was imported to Caesarea. Oleson and Branton have shown that in area G the basic ingredient of *pozzolana* came from the area around Vesuvius.[8]

Concrete remains at Caesarea, particularly in area K, have eroded severely, and the explanation is not entirely tectonic action or exposure to the sea. Layers of concrete have been eroded from within structures, and tunnels have formed, sometimes causing the overlying mass to collapse and break apart. Some layers within the blocks are weaker than the surrounding material. Working within the inner cell in K2 the excavators noted that the matrix was considerably softer and easier to dig out than the material outside the cell; they noted also that the concrete here had very little large aggregate.[9]

During the 1994 season divers took samples of concrete primarily from the remains of caisson K5. Surface marine concretions were cleaned, and the largest possible chunks of aggregate and mortar were carefully cut out intact from the concrete mass and bagged, sealed, and labeled underwater. The areas selected for sampling included the lower, middle, and top layers of K5 on the N, S, and E faces, as well as central locations. Samples were taken only from intact parts of the concrete mass. Also sampled, in order to make comparisons, were the concrete blocks to the north and east of K5 and in area U.

Petrographic analysis of the samples was undertaken to determine the make-up of the samples and to understand why there were variations in the strength of different parts of the blocks. As the samples were comparatively soft and crumbly, they were bound with resin prior to cutting. Slices from 5 of the samples were cut from the surface inward, and a thin section was prepared from each and examined under a petrographic microscope.[10] The samples representing

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internal framing and bracing, totalling 64 m^3 of timber, mainly pine. Assuming a bulk density of 500 kg per m^3 for the dry timber (containing only 15% moisture) and 650 kg per m^3 for partially saturated wood, the caisson would have weighed 32 tons on the beach where it was constructed and would have floated empty with a draft of 400 mm.

[6] E. K. Gazda,"The port and fishery: description of the extant remains and sequence of construction" in A. M. McCann, *The Roman port and fishery of Cosa* (Princeton 1987) 74-79.

[7] Vitruvius discusses the use of hydraulic concrete for building harbors at 2.5-6. Roman engineers and builders tended to use the purest limestone to make lime for mortar. This lime, which contained only 0.1-1.0% clay impurities, produced a non-hydraulic mortar; if they had used limestone with 8-20% clay, an aluminium silicate, however, they would actually have made a hydraulic lime. The addition of *pozzolana*, with high levels of silicate of alumina, to a non-hydraulic lime converts it to a hydraulic version. The same effect was achieved by adding crushed pottery, again because it contained an aluminium silicate.

[8] Oleson and Branton (supra n.1) 49-67.

[9] A. Raban, "Caesarea Maritima 1990: the underwater research," *Centre for Maritime Studies News* 17 (1990).

[10] Petrographic analysis of the concrete samples was carried out by Technotrade Limited of Harpenden, England. An area measuring approximately 24.5 cm2 was selected and cut from the core, then dried at

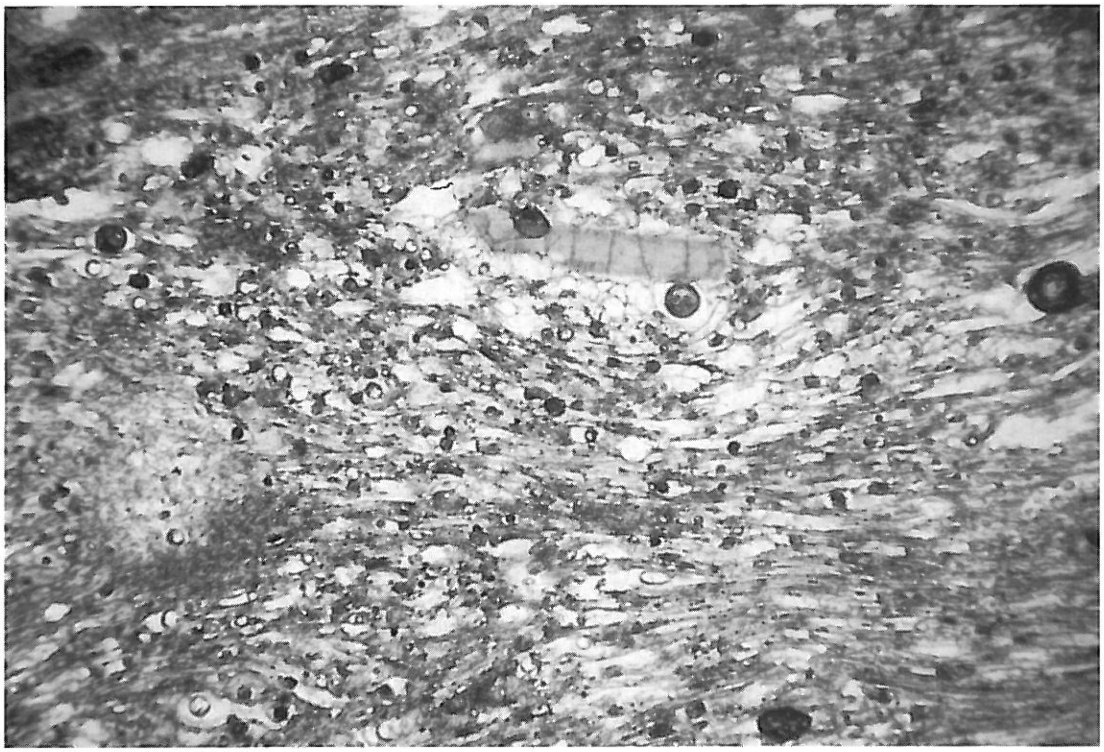

Fig. 6. Crossed polars petrographic slide of a sample of a *pozzolana* particle from the east face of base level of K5 (M. Grove).

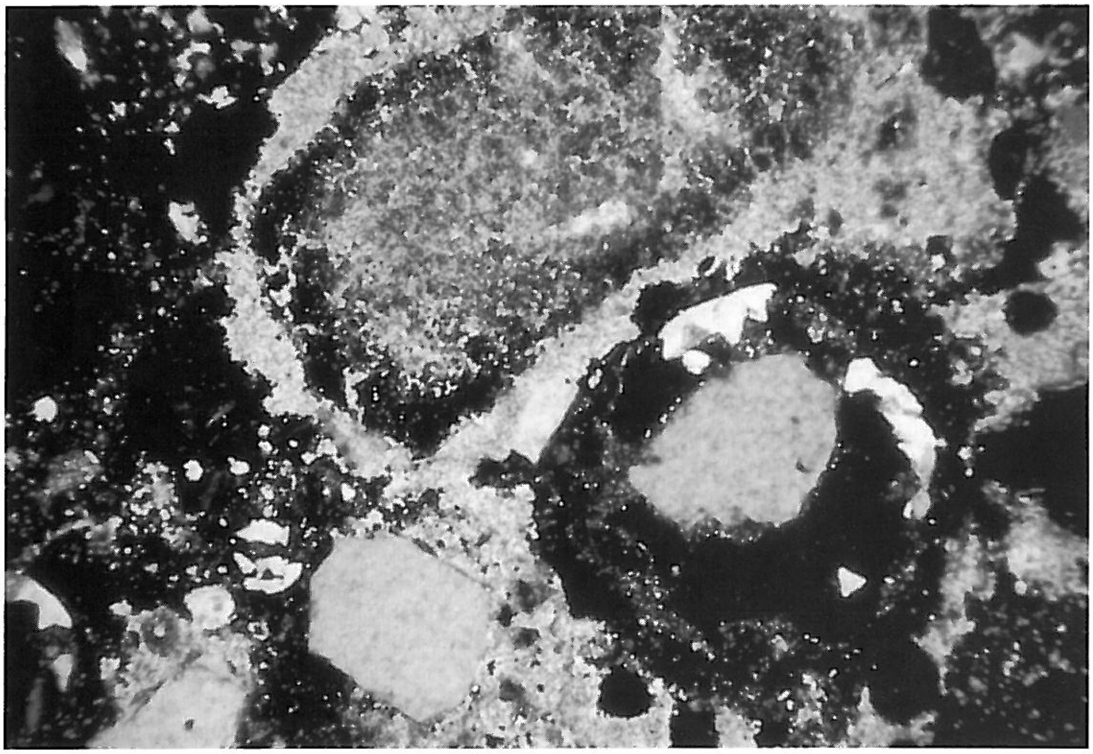

Fig. 7. Crossed polars petrographic slide of sample 17 from the south face of K5 taken 1 m above the base. The sample displays high lime content, low *pozzolana* content, and a core of hard burned lime, unhydrated (M. Grove).

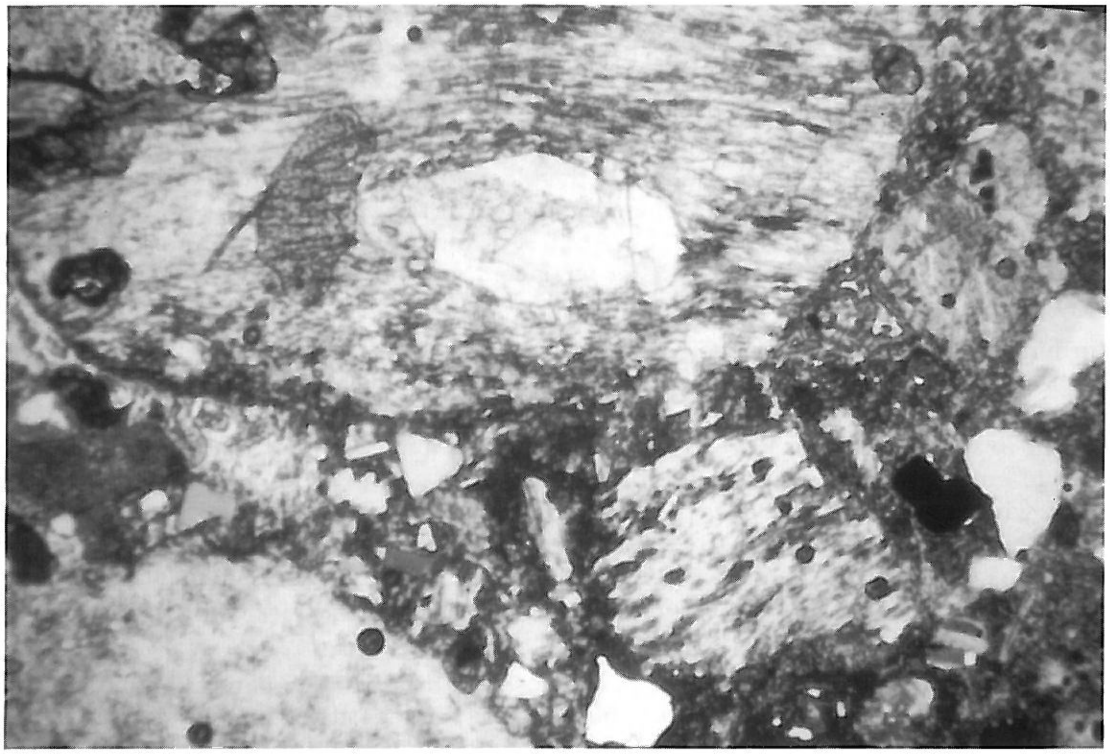

Fig. 8. Parallel polars petrographic slide of sample 16 with high *pozzolana* content and low lime content, from the base layer of K5 (M. Grove).

the upper and lower layers of the block were found to have a high volcanic tuff or *pozzolana* content and low levels of lime. Samples from the central layers were high in lime and had only a minimal amount of volcanic material. Although *pozzolana* and sand have similar chemistries, under the microscope *pozzolana* has a distinct glassy appearance with air voids (fig. 6), while sand has a clear crystalline appearance. Sample 17 (fig. 7), taken from the central area on the S face of K5, had a low *pozzolana* content but was high in lime, while sample 16 (fig. 8) which came from the base layer was proportionally higher in *pozzolana*.

During preparation of some samples with high lime content, including sample 16 (fig. 8), it was noticed that particles of burnt lime had not rehydrated. During sawing, with water being used as a coolant and lubricant, some of the particles hydrated rapidly, disrupting cutting of the sample. The reaction of such particles to hydration may have caused the degradation of the layer from which the sample came. The presence of unhydrated lime indicated that the mortar was less permeable than first thought. When hydrated, however, it tended to deteriorate rapidly. Clearly this concrete, which incorporated a considerable amount of non-hydraulic material, was not set in place underwater but was cast in a dry environment.

These concreted caissons were obviously a product of the techniques that Vitruvius describes for casting concrete in water, specifically his third technique of casting within a dry form.[11]

30C for several hours, before being vacuum impregnated with a coloured epoxy resin. The concrete slice was then reduced to a thickness of 30 microns by a series of grinding and polishing processes, and was finally sealed with a cover slip. The thin section was then examined under a combination of plain and cross-polarized light using a petrographic microscope. The majority of rocks are so finely crystalline that a microscope is necessary to allow precise identification of their mineral content. The extreme thinness of the section permits the various minerals to be distinguished according to their behavior in transmitted light. Polarising filters within the petrographic microscope produce cross-polarized light in which the crystals affect the light path and produce characteristic interference colors. This feature, together with other properties such as refractive index, crystal shape, and crystal texture, permit identification of almost all minerals and rock types.

[11] Vitr. 5.12: But in places where this powder is not found the following method must be employed. A cof-

Vitruvius recommends the use of this method where no *pozzolana* is available. This was obviously not the case at Caesarea, since large quantities of *pozzolana*-based concrete exist all around the harbour enclosure and also within the blocks of area K. Raban has suggested that these caissons were among the first elements installed in the Herodian harbour[12] and there may have been a shortage of *pozzolana* at the outset of the construction program; thus, while stocks were being built up, the architects or engineers may have reduced the need for it by following a variant of Vitruvius' third technique.[13]

Vitruvius describes the construction of watertight double-walled cofferdams around an area to be filled with concrete; the area is then pumped dry before the concrete (without *pozzolana*) is added. It would not have been feasible to construct a piled, double-walled, watertight cofferdam *in situ* at this exposed location. Ship construction techniques, however, made it possible to build rectangular watertight forms on shore and float them out partly filled with concrete, which functioned as ballast. Once they were at the prescribed site, the addition of concrete caused them to sink, but adequate freeboard was maintained to ensure that the interior remained dry.[14] The extensive internal bracing counteracted the hydrostatic load against the submerged structure, which rose no more than 2.5 m above the depth of the internal concrete mass.

There is little doubt that these structures were used in the Herodian harbour, although the evidence is not entirely clear. Beneath the south face of K3 deposits of 1st- and 2nd-c. sherds were found sealed beneath laminated layers of fine sand. It might be argued that the caissons were not Herodian but a later device to extend, repair, or reduce the width of the entrance channel, but this would not have required a series of single-mission barges meticulously constructed at great cost by skilled craftsmen with imported timber. The same result could have been achieved by simply dumping rubble from the end of the Herodian mole.

In another novel approach, instead of non-hydraulic concrete the builders used sand. They deliberately formed sand catchment enclosures to trap sand in suspension and build up embankments that could be sealed with masonry to form the base of the quays.[15]

The demise of the harbour

This confusing picture becomes clear only when one considers the demise of the harbour and its inherently flawed design. The single-mission barges of area K were a unique example of the

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ferdam with double sides, composed of charred stakes fastened together with ties, should be constructed in the appointed place, and clay in wicker baskets made of swamp rushes should be packed in among the props. After this has been well packed down and filled in as closely as possible, set up your water-screws, wheels, and drums, and let the space now bounded by the enclosure be emptied and dried. Then, dig out the bottom within the enclosure. If it proves to be of earth, it must be cleared out and dried till you come to solid bottom and for a space wider than the wall which is to be built upon it, and then filled in with masonry consisting of rubble, lime, and sand. (trans. Morgan [supra n. 7]).

[12] A. Raban, "The Herodian harbor of Caesarea: how it was built and operated," *Center for Maritime Studies News* 19 (1992).

[13] C. Brandon, "Cements, concretes, and settling barges at Sebastos" in *Caesarea retrospective* 25-40.

[14] The caisson would have floated when empty with a draft of 400 mm (supra n. 5). Filled with 50 cm of concrete, it would have floated with a draft of 1.5 m, assuming a bulk density of 2300 kg per m^3. Only a 1 m fill was required to cause the caisson to settle onto the seabed. Assuming a seabed depth of 3.5 m in antiquity and a caisson height of 4 m, the maximum height of structure exposed to hydrostatic forces was 3.5 - 1 = 2.5 m.

[15] Raban (supra n. 12) has described probes into sand deposits within the harbor enclosure that exposed accumulated layers of well-sorted grain-size sediments, demonstrating the variation in wave energy during the period of deposition. He suggests that 2-3 years were required for natural processes to silt up the pockets. Once filled, they were covered with a layer of rubble that sealed the captured sediments and served as a base for paving slabs of the promenade and floors of storage vaults on the quays.

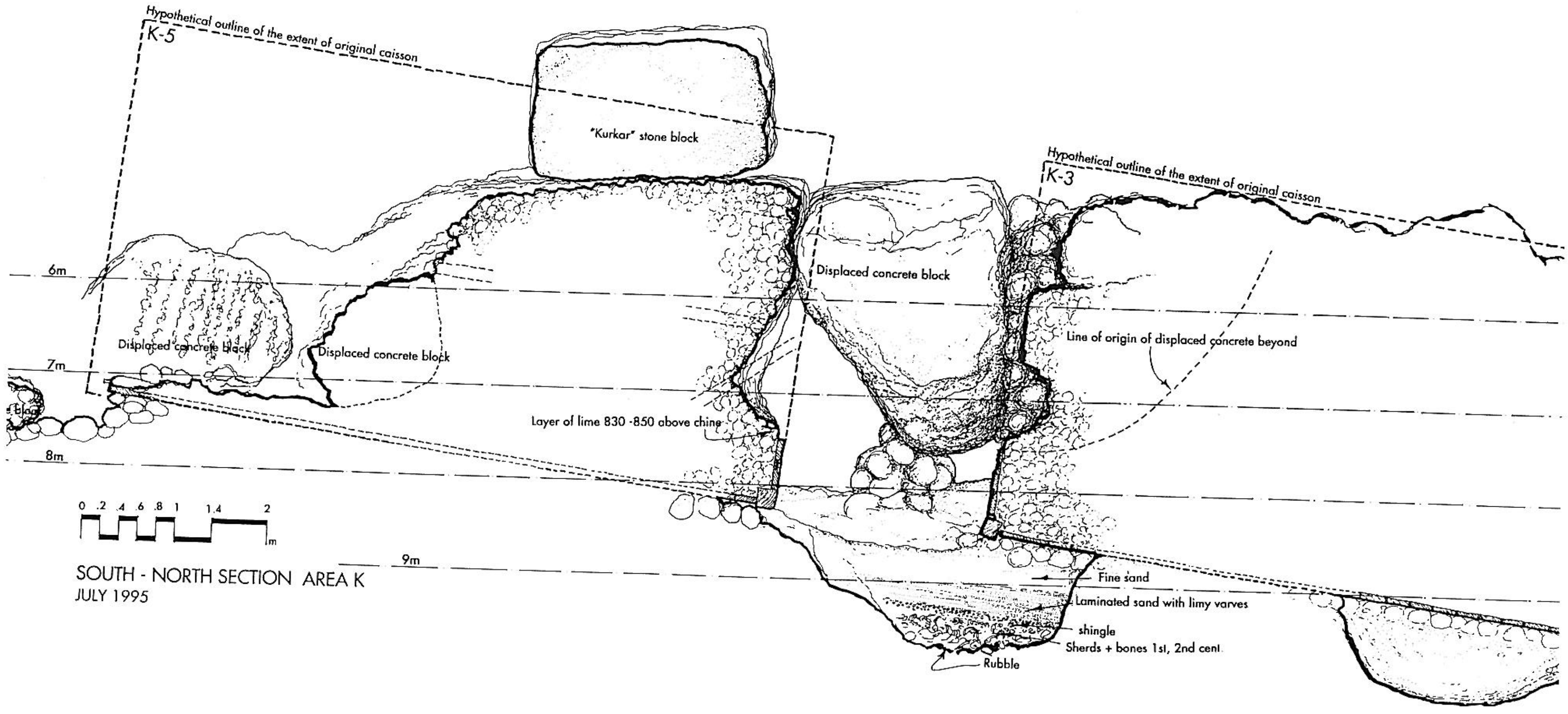

Fig. 9. S–N section through areas K3 and K5 showing deposits below south edge of K5 (C. Brandon).

ingenuity of Roman engineering but they failed because the engineers could not foresee that tectonic settling would occur in the area. Tectonic settling across the harbour was not the cause of their destruction but the trigger for it. Only minor tectonic activity was needed to begin the chain of events that would result in the collapse of the harbour enclosure. Breaches of the sand pockets would have allowed the sea gradually to undermine the overlying structures. This process might have taken only a few months, and was devastating when combined with overall settling of the seabed. Settling of the seabed in area K dislodged protective berms placed against the base of the submerged structures and exposed the concrete blocks to the force of the sea. Marine organisms soon stripped off the protective timber cladding, exposing the soft layers of lime-based mortar. Wave action gradually eroded the mortar, forming tunnels through the centre of the blocks. The loose fill between the caissons was dislodged and washed out as the blocks tilted to the north and east. Strong currents washed between the caissons, scouring and undercutting their southern edges by several meters. Erosion within the concrete eventually caused parts of the upper layers to collapse, sealing the gaps, allowing sand to build up, and trapping material that had been washed in and deposited below the undermined edges of the blocks (fig. 9).

These dramatic changes occurred between the later 1st and early 2nd c. Thereafter the harbour was beyond repair.[16] Sea-level gradually rose, drowning the collapsed structure. Erosion continued but at a slower pace, and sand sealed and preserved the lower layers, including the remaining timber formwork and trapped pottery.

Many questions remain unanswered, in particular how extensively the lime-based material was used within each caisson and what the distribution and nature of the large aggregate was. To study them will require extracting large diameter (10-15 cm) core samples from various layers and different blocks by means of a hydraulically-powered diamond drilling rig. In the meantime, ongoing investigation hopefully will throw more light on the purpose of the inner cell in K2 and determine whether it existed in other caissons as well.

Pringle Brandon Architects, London (C. Brandon);
Technotrade Limited, Harpenden (S. Kemp and M. Grove)
December 1995

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[16] In "Sebastos: the royal harbour at Caesarea Maritima, a short-lived giant," *IJNA* 21 (1992) 111-24, Raban proposed that the harbor's breakwater failed before the mid 3rd c. See now A. Raban *et al.*, "Underwater excavations (1993-94)" and "Land excavations in the Inner Harbour", both in this volume.